THE

ELECTRICAL NATURE

OF

MATTER AND RADIOACTIVITY

BY

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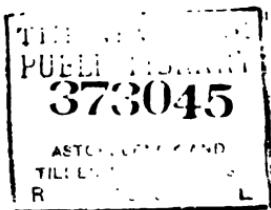
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PREFACE

THE content of this book has already been published as a series of articles in the *Electrical Review*. The two correlated subjects under consideration are of such general interest, that it has seemed desirable that the discussion of them should be made accessible in compact form.

The several chapters as they originally appeared have, therefore, been carefully revised, and brought together in one volume. The author would extend his sincere thanks to his assistant, Dr. H. S. Uhler, for a number of valuable suggestions in connection with the revision of the work.

The aim of the writer has been to present the more important facts and conclusions in connection with the work on the "Electrical Nature of Matter and Radioactivity," as far as possible in non-mathematical language. This has been done with the belief that there are a large number of those who have a truly scientific interest in these most recent and important developments in Physics and Physical Chemistry, but to whom a more technical and rigidly mathematical treatment might not appeal. To all who desire such a treatment, the admirable books by Thomson, on the "Conductivity of Electricity through Gases," and by Rutherford, on "Radioactivity," are heartily recommended.

While this work is written in a semi-popular style, the attempt has been made to treat the subject with scientific accuracy. The facts presented have nearly always been taken directly from the original sources. Since, however,

this is a comparatively elementary discussion, references to the original papers are given chiefly in the cases of the more important contributions. All of those who desire to go more fully into these subjects are urged to read as many as possible of the original articles.

If this little book should contribute even in a small measure towards supplying the general demand for knowledge in the field which it covers, it will more than repay for the time and labor that have been spent in its preparation.

HARRY C. JONES.

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ABBREVIATIONS OF THE TITLES OF JOURNALS

Amer. Chem. Journ. = American Chemical Journal.

Amer. Journ. Sci. = American Journal of Science.

Ann. Chim. Phys. = Annales de Chimie et de Physique.

Ann. d. Phys. = Annalen der Physik (Drude).

Ber. d. deutsch. chem. Gesell. = Berichte der deutschen chemischen Gesellschaft.

Cam. Phil. Soc. Proc. = Proceeding of the Cambridge Philosophical Society.

Chem. News = Chemical News.

Compt. rend. = Comptes rendus.

Journ. Chem. Soc. = Journal of the Chemical Society of London.

Journ. de Chim. Phys. = Journal de Chimie Physique.

Nat. = Nature.

Phil. Mag. = Philosophical Magazine.

Phil. Trans. = Philosophical Transactions of the Royal Society.

Phys. Rev. = Physical Review.

Phys. Zeit. = Physikalische Zeitschrift.

Roy. Soc. Proc. = Proceedings of the Royal Society.

Wied. Ann. = Wiedemann's Annalen.

Zeit. phys. Chem. = Zeitschrift für physikalische Chemie.

The Electrical Nature of Matter and Radioactivity

CHAPTER I

THE ELECTRICAL CONDUCTIVITY OF GASES

THE power of gases, under normal pressure and at ordinary temperatures, to conduct electricity is so small that it has been doubted whether pure, dust-free gases can conduct at all. Recent refined experiments, however, show that while pure, dust-free gases have only a small conductivity, they have a definite power to conduct electricity, which is measurable.

CONDITIONS WHICH INCREASE THE CONDUCTIVITY OF GASES

While gases under normal conditions have only slight conductivity, and are fairly good insulators, it is not a difficult matter to increase greatly the conductivity of gases. This can be done in a number of ways. When gases are heated to high temperatures their electrical conductivity is greatly increased. According to Becquerel, when air is heated to a white heat, electricity will pass through it when the difference in potential is small. It is also known that gases in contact with incandescent solids have their conductivity increased. Some interesting and important facts, which it would lead us too far at present to discuss, have been brought to light through the study of these phenomena.

Gases taken from flames have been found to show considerable conductivity, which is retained for some time after the gas has been removed from the flame and cooled down.

Other agents which increase the conductivity of gases are Röntgen rays, the presence of radioactive substances, and cathode rays. As these will be taken up later in some detail, they will not be discussed further in the present connection.

HOW A CONDUCTING GAS DIFFERS FROM A NON-CONDUCTING

We have seen that a gas in the normal condition has very small power to conduct electricity.

We have also seen that the conducting power of a gas can be greatly increased by a number of widely different agents. The question that would naturally arise in this connection is, how does a conducting gas differ from a non-conducting or normal gas? (We may term a normal gas non-conducting, since its conductivity is so slight.)

To answer this question we must study the properties of a conducting gas, and compare them with the properties of a non-conducting gas.

If the conducting gas is made to pass through a plug of glass-wool, or is drawn through water, it loses its conducting power. The conducting power of a gas is also removed by passing the gas through a metal tube of very fine bore; the finer the bore the more rapidly the conductivity is lost.

The removal of the conducting power by filtering through glass-wool shows that the conductivity of the gas is due to some constituent which is filtered out mechanically by the glass-wool. The experiments with the metal tube show that this constituent which can be filtered out by glass-

wool is charged with electricity. These charged particles in a conducting gas are known as *ions*. Some of these particles are charged positively and others negatively. Since a conducting gas shows neither an excess of positive nor of negative electricity it is, as we say, electrically neutral.

THE RATIO OF THE CHARGE TO THE MASS OF THE ION IN A GAS

When an acid, base, or salt is dissolved in water, we know that it breaks down into charged parts called ions. Every molecule of an electrolyte yields an equivalent number of positively charged parts or cations, and negatively charged parts or anions. The ratio of the charge carried by these ions to their mass has been determined. In the case of the hydrogen ion, which is the characteristic ion of all acids, it has been found to be of the order of magnitude of 10^4.

It was recognized to be of importance to determine the ratio of the charge to the mass of the ion in gases. If we represent the charge carried by the gaseous ion by e, and the mass of the ion by m, the ratio in question is $\frac{e}{m}$.

We shall take up first the determination of the ratio $\frac{e}{m}$ for the cathode particle.

THE CATHODE RAY

When an electric discharge is passed through a high-vacuum tube, rays are sent out from the cathode which generally produce a greenish yellow phosphorescence where they fall upon the glass walls of the tube. These are known as the cathode rays. The nature of these rays was for some time in doubt. It was thought by some investigators, that they were waves in the ether. It remained for Sir William

Crookes to give us the accepted explanation of the nature of the cathode rays. According to Crookes the cathode rays are charged particles, sent off from the cathode with very high velocity. They move towards the anode in a direction at right angles to the surface of the cathode. The properties of the cathode rays, in general, are in accord with this theory. The cathode rays can be deflected by a magnet.

A solid body placed in their path casts a well-defined shadow.

Cathode rays can probably produce certain chemical changes, especially of a reducing nature.

Mechanical effects can readily be produced by the cathode rays, as was shown by Sir William Crookes. A glass paddle-wheel is easily made to move along level glass tracks within the tube, by allowing the cathode rays to impinge upon the vanes.

Thermal effects are readily produced by the cathode rays. By suitably concentrating them upon platinum, the metal is rendered incandescent. All of these facts accord with the theory as to the nature of the cathode rays, advanced by Sir William Crookes.

The discovery that cathode rays can pass through thin films of metal seemed at first to argue against the Crookes theory. When we become familiar later with the exact nature of the cathode particle itself, we shall see that this argument is without foundation.

We shall, then, at present accept the Crookes theory, and regard the cathode rays as consisting of negatively electrified particles, moving with high velocities, in straight lines at right angles to the surface of the cathode.

In the light of the above theory and the facts upon which it is based, we shall now take up the work of J. J. Thom-

son, by which he determined the value of $\frac{e}{m}$ for the cathode particle.

THE VALUE OF $\frac{e}{m}$ FOR THE CATHODE PARTICLE

The value of $\frac{e}{m}$ for the cathode particle was determined by J. J. Thomson,[1] as follows: The cathode is placed near one end of an exhausted tube, and the anode removed only a short distance from the cathode. Beyond the anode on the side removed from the cathode is placed a metal plug connected with the earth. A small hole is bored through the centre of the anode and the metal plug. Cathode rays pass through these holes and fall on the wall of the vacuum tube at the end of the tube farthest removed from the cathode. Since the holes in the metal plates are small, we have a narrow beam of cathode rays striking the inner wall of the glass vessel, forming a small, phosphorescent spot on the glass.

We have seen that the cathode rays are deviated by a magnetic field. If the whole tube is now properly placed in a magnetic field, the path of the cathode particles will be changed, and they will impinge upon the glass wall at some point different from that which they originally bombarded when no magnetic field was present. Measuring the magnitude of this deflection we can calculate the value of $\frac{e}{vm}$, in which v is the velocity of the ion.

We have thus determined the ratio of e to vm.

We must now determine the value of v in order to obtain the ratio $\frac{e}{m}$.

Into the above-mentioned vacuum tube are inserted

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[1] Phil. Mag., **44,** 293 (1897).

two parallel plates of aluminium, which are so arranged that the beam of cathode particles passes between them. The plates are also parallel to the original, undeflected beam. These metal plates are attached to some electrical source, and maintained at a known difference in potential. We thus have between the plates an electric field. The electrostatic intensity s, due to this field, deflects the ion with a force se, e being the charge upon the ion. The force due to the magnetic field already considered is fev, f being the strength of the field, e the charge carried by the ion, and v the velocity of the ion.

By suitably charging the metal plates, the electrical and magnetic forces can be made to act counter to one another. These two counter forces can readily be made equal to each other. This can easily be determined. We note the original position of the phosphorescent spot on the glass before placing the apparatus in the magnetic field. When the apparatus is placed in the magnetic field the beam of cathode particles is deflected, and the bright spot on the glass changes its position. The electrostatic force acting counter to the magnetic, causes the beam to occupy more nearly its original position. When these two opposing forces are equal the phosphorescent spot occupies its original position. Thus, we have an easy and efficient means of determining when these two opposite forces are equal. When they are; $fev = se$.

Knowing now the value of v, and having previously determined, as we have seen, the ratio of e to vm, we have the value of $\dfrac{e}{m}$, which is the quantity desired.

THE RATIO $\frac{e}{m}$ CONSTANT FOR DIFFERENT GASES

Using a somewhat different method, J. J. Thomson found at first that *the ratio $\frac{e}{m}$ was a constant, whether the gas in the tube was air, carbon dioxide, methyl iodide or hydrogen.* This is a most important fact, as we shall see.

Thomson and his coworkers then changed the nature of the metal of which the cathode was made, using platinum, aluminium, silver, copper, tin, zinc, lead, and iron, to see whether the nature of the metal from which the cathode discharge takes place has any effect on the value of the ratio $\frac{e}{m}$. *They found the same value for $\frac{e}{m}$, regardless of the nature of the metal of which the cathode was made.*

Thomson found that the value of $\frac{e}{m}$ was equal to about $1 \times 10.^{7}$

THE RATIO $\frac{e}{m}$ VARIES FOR THE DIFFERENT IONS OF ELECTROLYTES

It will be seen that the value of $\frac{e}{m}$ for the ions of electrolytes varies with every kind of ion. This is necessarily the case, since the charge carried is the same for all univalent ions (and this quantity multiplied by the valency for all polyvalent ions, as is seen from Faraday's law), and the mass varies with every cation and every anion. Taking the ion characteristic of acids, hydrogen, the value of $\frac{e}{m}$ for the hydrogen ion is 1×10^{4}.

It is therefore obvious that the *value of $\frac{e}{m}$ for the cathode*

particle is one thousand times as great as the corresponding value for the hydrogen ion produced when any acid is dissolved in a dissociating solvent.

Knowing the values of $\frac{e}{m}$ in the two cases does not tell us anything about the relative masses of the hydrogen ion in solution, and the particle in the cathode discharge; since the charges carried in the two cases might be the same or might be very different. Before answering this question we must know the relative charges carried by the ion in electrolysis, and by the cathode particle.

THE VALUE OF $\frac{e}{m}$ FOR GASEOUS IONS PRODUCED BY DIFFERENT MEANS

Before taking up the beautiful method for determining the value of the charge carried by the cathode particle, we shall ask and answer the question whether the value of $\frac{e}{m}$ for gaseous ions is the same, regardless of the means by which the gaseous ions are produced, or whether it varies with the means employed to produce the ions in the gas?

The answer to this question is unmistakably given by the results that have been obtained. The Lenard rays are nothing but cathode rays that have left the so-called vacuum tube by passing through a thin sheet of aluminium. The value of $\frac{e}{m}$ for the particles in these rays has been found to be about 4×10^6.

The value of $\frac{e}{m}$ for the gaseous ions produced in contact with incandescent metals is about 8.5×10^6.

The value of $\frac{e}{m}$ for the negative ion given off from radio-active substances is about 1×10^7.

It is obvious that the above values all refer to the negative, gaseous ion. We see from the results that the value of $\frac{e}{m}$ for this ion is practically constant, regardless of the means by which it is produced, and regardless of the nature of the gas from which it is produced.

As to the value of $\frac{e}{m}$ for the positive ion of gases, we shall have something to say in the next chapter, and shall also discuss the nature of this ion.

CHAPTER II

The Determination of the Mass of the Negative Ion in Gases

WORK OF J. J. THOMSON

THE determination of the charge carried by the negative ion is of the very greatest importance. We have already considered the method for determining the ratio $\dfrac{e}{m}$ for the negative ion. If we can now determine e, the charge carried by this ion, we would know m, the mass of the negative ion.

One of the most ingenious experiments in modern physics has been devised by J. J. Thomson for solving this problem. The experiment is based on an observation made by C. T. R. Wilson,[1] that gaseous ions, both positive and negative, can act as nuclei for the condensation of water-vapor, even if there are no dust particles present in the gas. If a given volume of a gas containing ions is allowed to expand, it cools itself, and a part of the water-vapor will condense around the ions, producing a fog or cloud in the apparatus containing the gas.

That the water-vapor actually condenses around the ions was proved conclusively by J. J. Thomson, by the following very simple experiment. Two parallel metal plates were placed a few centimetres apart in the vessel containing the gas which had been freed from dust. These

[1] Phil. Trans., A., 265 (1897).

plates were connected with the terminals of a battery, by which they could be charged to a relatively high difference in potential. Ions were produced in the gas by passing Röntgen rays through it.

If the gas was expanded before the plates were connected with the battery, condensation of the vapor took place; just as we should expect if the ions acted as nuclei around which the water-vapor would condense. If the plates are now connected with the battery and charged, the strong electrical field would remove the ions from the gas, and if the gas were then subjected to expansion we would not expect any appreciable condensation to take place, and such is the fact. Thomson says that under these conditions the condensation is scarcely greater than in unionized air.

This experiment shows conclusively that it is the ions that serve as the centres of condensation of the water-vapor — a drop of water condensing around every ion if the ions are not too numerous. If we knew the number of droplets of water in a given volume of the gas, we would know the number of ions in that volume. It is, however, obviously impossible to determine the number of water particles in a volume of gas by any direct method. Thomson [1] solved this part of the problem by using an equation deduced by Stokes, connecting the rate at which the particles fall with their size. If we represent by v the velocity with which the particles fall, by g the acceleration of gravity, by c the viscosity coefficient of the gas, and by r the radius of the drop,

$$v = \frac{2}{9}\frac{gr^2}{c}$$

By observing the rate at which the cloud settles we arrive

[1] Phil. Mag., 46, 528 (1898).

at the value of v. Knowing v we determine at once the value of r, the radius of the drop. Knowing the radius of the drop we know its volume.

If we represent the mass of the water deposited by each cubic centimetre of the gas, by M, the number of drops in a cubic centimetre n is given by the following equation:

$$n = \frac{3M}{4\pi r^3}$$

The mass of water deposited from each cubic centimetre of the gas, M, must be determined indirectly. Thomson made use of the heat that is liberated when the water-vapor condenses around the gaseous ions. Knowing M and r we have all the data necessary for calculating n, the number of ions in a cubic centimetre of the gas, which is equal to the number of droplets in the same volume.

We now know the number of ions in a given volume of the gas. It still remains to determine the charge carried by a single ion.

If we knew the total quantity of electricity carried by the known number of ions, we would know the amount carried by one ion. Let v be the mean velocities of both positive and negative ions when subjected to unit electrical force. We must measure the current carried by these ions across unit area, under an electric force F, in order to determine the charge carried by a single ion. If we represent the charge carried by a single ion as formerly by e, we have; $Fvne$ = current through unit area perpendicular to the current. Measuring the current that passes through the gas, we know all of the above quantities except e, which is calculated at once.

In performing the condensation experiment it is neces-

sary, as Thomson points out, to work with gases which contain only a comparatively small number of ions. When the conducting gas contains a large number of ions some of these are not carried down by the condensed water-vapor, as is shown by the fact that under these conditions a second expansion of the gas, which is no longer subjected to the ionizing agent, will produce still further condensation, demonstrating that it still contains ions that were not carried down by the first expansion.

The condition that the gas shall contain only a few ions is easily secured, especially when the gas is ionized by Röntgen rays. Either a weak stream of the rays is allowed to pass directly through the gas, or the intensity of the rays is diminished by inserting thin sheets of certain metals, such as aluminium, in their path.

The earlier experiments showed that the values of e for air ionized by Röntgen rays, and for hydrogen gas ionized by Röntgen rays, are equal to within the limit of experimental error, which proves that the gaseous ion carries the same charge whatever the gas from which it was produced. It is of the order of magnitude 4×10^{-10}.

COMPARISON OF THE CHARGE ON A GASEOUS ION WITH THAT ON A UNIVALENT ION OF AN ELECTROLYTE

Having determined the magnitude of the charge on a gaseous ion, we shall next determine the magnitude of the charge carried by a univalent ion of an electrolyte — say the hydrogen ion.

We know that the number of molecules in a cubic centimetre of a gas, at a pressure of 760 millimetres of mercury and at zero degrees, is between 2×10^{19} and 1×10^{20}. We know the amount of electricity required to liberate this

amount of hydrogen gas. From these data we calculate that the charge carried by the hydrogen ion in solution is somewhere between 1×10^{-10} and 6×10^{-10}.

We thus see that the *charge carried by the gaseous ion is the same as that carried by the hydrogen ion in electrolysis.*

This conclusion is based upon a large amount of work with the ions produced from various gases and by various ionizing agents. We have already seen that *the value of* $\frac{e}{m}$ *for all of these gaseous ions is the same, no matter what the nature of the gas from which they were produced,* and no matter what the nature of the ionizing agent. It has further been shown that all of these gaseous ions carry the same charge, and that this is the same charge as that carried by the hydrogen ion in aqueous solution.

We have now all the data necessary for calculating the relative masses of the gaseous ion, and the hydrogen ion in solution.

The value of $\frac{e}{m}$ for the hydrogen ion in solution is 10^4.

The value of $\frac{e}{m}$ for the gaseous ion is 10^7. The values of e in the two cases are the same. *Therefore, the value of m for the gaseous ion is about one-thousandth the value of m for the hydrogen ion in solution.*

More accurate determinations show that the relation between the masses of the gaseous ion and the hydrogen ion in solution is as 1 to 770.

It is difficult to overestimate the importance of this conclusion. In the first place, it is a matter of the very highest importance to establish the fact that the mass of the gaseous negative ion is always the same, no matter what the nature of the gas from which this ion is split off, and no matter

what the nature of the ionizing agent. This has been shown to be true whether the gas is elementary or compound. This shows that a *common constituent can be split off from all gases no matter how widely they may differ chemically*, and what is perhaps even more important is that the *mass of this negative ion which can be split off from any gas is much less than the mass of the lightest so-called element known to the chemist*. The gaseous negative ion is, then, a common constitutent of all matter, and is much smaller than the smallest atom known to the chemist, having a mass which is only about $\frac{1}{770}$ of that of the hydrogen ion in solution, which, as we shall see, has practically, but not exactly the same mass as the hydrogen atom.

This unit of matter, so much smaller than the atom, and which is apparently common to all atoms, carrying a unit, negative electrical charge or that charge carried by the chlorine ion in solution, Thomson called a *corpuscle*.

THE RATIO OF THE CHARGE TO THE MASS FOR THE POSITIVE ION

Before leaving this part of our subject a few words should be added in relation to the value of the ratio $\frac{e}{m}$ for the positive ion. These positive ions exist in the so-called *canal rays*, discovered by Goldstein. They are also known as anode rays. Just as the cathode rays move from the cathode towards the anode, so there is a corresponding movement of matter towards the cathode. This can be detected by perforating the cathode with a number of holes, through which the canal rays pass, and produce a phosphorescence where they fall on the walls of the glass tube behind the cathode.

Wien used a perforated cathode of iron, and determined

the value of $\frac{e}{m}$ for the rays which passed through his cathode. He used the method already described for determining the value of $\frac{e}{m}$ for the cathode particles. He deflected the rays by means of a strong magnetic field, and then in the opposite direction by means of an electrostatic field. A strong magnetic field is necessary to produce an appreciable deflection of the canal rays, and this renders the result less accurate. He obtained the following result:

$$\frac{e}{m} = 3 \times 10^2.$$

He also found that these positively charged particles move with much smaller velocity than the negatively charged particles.

If we compare the value of $\frac{e}{m}$ for the negatively charged particle with that for the positively charged iron particle, we shall see that the value for the negatively charged particle is about 3.3×10^4 times the value for the positively charged particle.

Since the electricity carried by the positively charged particle is the same in quantity as that carried by the negatively charged particle, it follows that the mass of the positive particle is of the same order of magnitude as that of the corresponding ion in solution.

We can, then, conclude that while the mass of the negatively charged particle in a gas is constant, independent of the nature of the gas, and very small as compared even with the mass of the lightest atom or ion in solution, the *mass of the positively charged particle is of the same order of magnitude as the corresponding atom or ion in solution in a dissociating solvent.* The mass of the positively charged

particle is not constant for different gases, but, as we should expect if the positive ion is a charged atom, varies with the nature of the gas in question.

This beautiful work of Thomson on the conduction of electricity through gases, makes it more than probable that a small particle which he calls the corpuscle is split off from the atoms of all gases, carries the negative charge, and is the same unit, no matter what the nature of the atom from which it separates.

The remainder of the atom from which the corpuscle has separated carries the positive charge, and is the positively charged ion in the gas. The *nature of this positive ion is different for every gas, being simply the atom minus the constituent common to all atoms, which is the corpuscle.*

It would be a tremendous step forward towards the solution of one of the greatest problems with which men of science have had to deal — *the ultimate nature of matter* — had Thomson gone no farther than what has been above developed. This is, however, but the beginning. Thomson has studied the nature of the corpuscle itself, and the result of this part of his investigation is certainly one of the most fascinating, and probably one of the most valuable contributions to modern science.

CHAPTER III

NATURE OF THE CORPUSCLE — THE ELECTRICAL THEORY OF MATTER

THE conception of the corpuscle as originally advanced is that it is a small piece of matter having a mass about $\frac{1}{770}$ of that of the hydrogen atom, and carrying a unit negative charge of electricity, which is exactly the same as that carried by any univalent anion, such as the chlorine ion in solution. The corpuscle is thus both material and electrical in its nature.

We shall now take up Thomson's study of the corpuscle itself, and see how the original conception has been modified, and the reasons for the view that we hold at present.

Let us first ask what reason have we for supposing that the corpuscle contains any matter at all? How do we know that it is anything but electricity? The answer would be that the corpuscle has both mass and inertia, and, therefore, must contain matter, since matter only has these properties. We shall now see whether this line of reasoning is valid.

WORK OF THOMSON AND KAUFMANN

In a paper published a number of years ago, J. J. Thomson at least raised the question as to whether inertia itself is not of electrical origin. The mass of a charged sphere would, in this case, be greater than that of the same sphere when uncharged.

Thomson showed that the particle must move very rapidly in order to have appreciable changes in its mass. Indeed, it must move with a velocity which is comparable with that of light, in order to produce measurable changes in its mass.

While the ordinary cathode rays move with a velocity that is only about 3×10^9 centimetres per second, the particles shot off from radium have a velocity as high as 2.8×10^{10}, which is nearly that of light itself $= 3 \times 10^{10}$. If the velocity with which the charge moves has any effect on its apparent mass, we should expect that the mass of these rapidly moving particles would be greater than that of the same particles when moving less rapidly. This question has been answered by the experiments of Kaufmann.[1] He determined the value of $\frac{e}{m}$ for these more rapidly moving particles, by means of the method already described, using the magnetic and electrical deflections. He found values as low as 0.63×10^7 for the most rapidly moving particles. Since e is constant, the charge being the same independent of the velocity, it follows that the mass of the rapidly moving, charged particle is greater than that of the more slowly moving, charged particle.

Kaufmann's experiments went farther. By means of the electrical and magnetic deflections, he determined the values of $\frac{e}{m}$ for the β particles shot off from radium with different velocities. We shall learn that these are essentially cathode ray particles. He obtained the following results. The velocities v are divided by 10^{10}, and the values of $\frac{e}{m}$ by 10^7, for convenience. The figures give us the relative values, which are all that we desire at present:

[1] Phys. Zeit., 4, 54 (1902).

v	$\dfrac{e}{m}$
2.36	1.31
2.48	1.17
2.59	0.975
2.72	0.77
2.83	0.63

It is obvious from the above data that as the velocity of
the charged particle increases, the value of $\dfrac{e}{m}$ decreases.
Since the value of the charge, e, remains constant, inde-
pendent of the velocity, it follows that the mass m becomes
greater and greater as the velocity of the charged particle
becomes greater.

The experiments of Kaufmann show conclusively that
the mass of a charged particle changes with the velocity of
the particle, increasing as the velocity increases.   In a
word, a *part of the mass of the particle, at least, is of electrical
origin.*

This would naturally raise the question, what part of
the mass is electrical?   Is it possible that all mass is elec-
trical?   Thomson has thrown light on this question in the
following manner.   When the corpuscle moves slowly the
mass, as we have seen, does not depend on the velocity,
and does not, therefore, change with the velocity.   When,
on the other hand, the velocity of the corpuscle approaches
the velocity of light, the mass varies with the velocity, as
is shown by the results of Kaufmann.   Assuming that the
entire mass of the corpuscle is of electrical origin, Thom-
son has calculated the variation of the masses of the
particles with the velocity.

The agreement between the calculated and observed

values is surprisingly good. This is a strong argument in favor of the correctness of the assumption on which the calculation is based.

If the whole mass of the corpuscle is electrical, why assume that the corpuscle contains any so-called matter at all? All of the properties of the corpuscle, including the two properties that we have been accustomed to associate with matter, inertia· and mass, are accounted for by the electrical charge of the corpuscle. Since we know things only by their properties, and since all of the properties of the corpuscle are accounted for by the electrical charge associated with it, why assume that the corpuscle contains anything but the electrical charge? It is obvious that there is no reason for doing so.

The corpuscle is, then, nothing but a disembodied electrical charge, containing nothing material, as we have been accustomed to use that term. It is electricity, and nothing but electricity. With this new conception a new term was introduced, and, now, instead of speaking of the corpuscle we speak of the *electron. The electron is, then, a disembodied electrical charge, containing no matter, and is the term which we shall hereafter use for this ultimate unit, of which we shall learn that all so-called matter is probably composed.*

If the electron contains nothing that corresponds to our ordinary conception of matter, and since the same electron can be split off from the atoms or molecules of all substances, the question naturally arises, is not all so-called matter made up of these electrical charges or electrons? Is not all matter of an electrical nature? There is a large amount of evidence, part of which has already been given, which answers this question in the affirmative. Indeed, this conclusion is accepted, at least tentatively, by a large

number of the leading physicists and physical chemists the world over.

THE ELECTRON THE ULTIMATE UNIT OF MATTER

According to the above theory the electron is the ultimate unit of all matter. The atoms are made up of electrons or disembodied electrical charges, in rapid motion; *the atom of one elementary substance differing from the atom of another elementary substance only in the number and arrangement of electrons contained in it.* Thus we have at last the ultimate unit of matter, of which all forms of matter are composed; and the remarkable feature is, that this ultimate unit of which all matter is composed is not matter at all, as we ordinarily understand that term, but electricity.

This recalls a paper published a number of years ago by Ostwald,[1] on "The Overthrow of Scientific Materialism," which made an impression at the time that it appeared, or rather a number of impressions. The arguments and conclusions in this paper were accepted by some without question, and were severely criticised by others, especially by the mathematical physicists of Germany. Whatever our opinion of the paper as a whole, there is one point at least brought out so clearly that there can scarcely be any question about it, and that is, that matter is a pure hypothesis.

What we know in the universe, and all that we know, is changes in energy. In order to have something to which we can mentally attach the energy, we have created, in our imagination, matter.

Matter, then, is a pure hypothesis, and energy is the only reality. We are accustomed to take exactly the opposite view, and regard matter as the reality and energy as hypothetical. If Ostwald accomplished nothing else by the

[1] Zeit. phys. Chem., **18**, 305 (1895).

paper in question than the mere calling attention to the hypothetical nature of matter, he made an important contribution to science.

It should also be noted that for a long time Ostwald has insisted not only that matter is a pure hypothesis, but there is not the least evidence for its existence, as we ordinarily understand the term. It is interesting to note that Thomson has reached the same conclusion, as the result of one of the most brilliant series of experiments that has ever been carried out in any branch of experimental science. We thus have a direct experimental verification of a conclusion, the importance of which it is difficult to overestimate.

EARLIER ATTEMPTS TO UNIFY MATTER

Perhaps the most important bearing of the electron is that it furnishes us with the ultimate basis of all matter. The importance of securing such an ultimate unit is shown by the number of attempts that have been made in this direction. One of the first noteworthy efforts we owe to the chemist Prout. After fairly accurate determinations of the atomic weights of a number of the more common elements had been made, it appeared that when these values were expressed in terms of the atomic weight of hydrogen as unity, they were all nearly whole numbers. Indeed, the deviations at first discovered were hardly greater than the experimental errors.

This led Prout, as early as 1815, to propose the theory that hydrogen is the ultimate element, of which all other elementary substances are made. The atoms of all other elements are simply condensations of hydrogen atoms, the number of hydrogen atoms contained in an atom of any element being expressed by the atomic weight of the element in terms of hydrogen as unity.

This hypothesis of Prout accounted for all the facts that were known at the time when it was proposed, and it is a praiseworthy attempt to solve the problem of the relation between the various chemical elements.

As experimental methods became more refined, and atomic weights more accurately determined, it gradually became obvious that the atomic weights of even some of the more common elements are not whole numbers in terms of hydrogen as one, but differ very appreciably from whole numbers. Indeed, the atomic weights of some elements fall almost half-way between whole numbers. This was, of course, a deviation too large to be accounted for on the basis of experimental error, and was, therefore, the death blow to the hypothesis of Prout as it was originally proposed by its author.

Subsequent suggestions by Marignac and others to make the half-atom of hydrogen, or even the quarter-atom, the basis of all matter, did not increase scientific respect for the hypothesis of Prout. Having once begun to divide the hydrogen atom the process could be continued indefinitely, and thus the theory could be, and was for a time, brought into disrepute.

It must not, however, be forgotten that if to-day we take those chemical elements whose atomic weights are most accurately determined, and calculate the atomic weights on the basis of oxgyen = 16, which is the system now in general use, we shall find that a very large proportion of the atomic weights are so close to whole numbers that the deviations can be accounted for on the basis of probable experimental errors.

Such an examination was recently made by Strutt,[1] who pointed out that the number of elements whose atomic

[1] Phil. Mag., **1**, 311 (1901).

weights are whole numbers is many times too large to be accounted for on the basis of chance.

Taking all of the facts into account, we recognize, of course, that the hypothesis of Prout, either as originally proposed, or as subsequently modified, is not rigidly true; but we still feel intuitively that there is something in it. The coincidences are far too numerous to be attributed to mere chance.

OTHER RELATIONS BETWEEN THE ELEMENTS

A number of other attempts have been made to point out relations between the atoms of the different chemical elements, with the hope of finding something in common between them. Döbereiner early noticed that of three closely related chemical elements, the atomic weight of the second heaviest element is almost exactly the mean of the atomic weights of the lightest and heaviest elements of the group of three. A few examples will make this clear. Take the three elements, calcium, strontium and barium. The atomic weight of calcium is 40.1; the atomic weight of barium is 137.4. The mean of these two values is 88.7, and the atomic weight of strontium is 87.6. To take an example from the negative elements, the above being taken from the positive, let us choose sulphur, selenium and tellurium. The atomic weight of sulphur is 32.1; that of tellurium 127.6. The mean of these two values is 79.8, while the atomic weight of selenium is 79.2.

Relations such as these are, of course, purely empirical, and their meaning is entirely unknown, yet they are, to say the least, suggestive.

We now come to the great generalization of Newlands, Mendeléeff, and Lothar Meyer, known as the Periodic System. This is the only attempt thus far made to coör-

dinate all of the chemical elements into one comprehensive system. The system is too well known to be discussed at any length in the present connection. It is referred to here to call attention to the most serious effort that has ever been made to discover general relations holding for all of the chemical elements.

It is well known that in the Periodic System the chemical elements are arranged in the order of their increasing atomic weights. It is not only found that the chemical and physical properties of the elements are a function of their atomic weights, but a periodic function of the atomic weights. If we arrange the elements according to the above principle, in groups of seven, allowing the eighth element to fall under the first, it is well known that the elements with chemically allied properties will fall in the same vertical columns.

It would lead us too far in this connection to point out the many and interesting chemical relations brought out by the Periodic System, and, perhaps, what is even more important, the relations between the atomic weights of the elements and their physical properties. It is sufficient to note here that such relations do exist, and that these are of a general character, embracing practically all of the elements known to the chemist.

The writer is in no sympathy with the attempt that is being made in certain directions to belittle and cast into the background the Periodic System. Of course, every one must recognize that the system is incomplete. Indeed, it is not only far from being complete, but leads in places to inconsistencies. Yet the Periodic System is a great generalization, which coördinates an enormous number of otherwise disconnected facts, and has done more towards placing inorganic chemistry upon a scientific basis than all the other generalizations together, that were proposed up to

1886. Indeed, it was the philosophy of inorganic chemistry for a comparatively long period, and has far from lost its usefulness at present. As we shall see, it again comes to the front in connection with the electron theory of matter that we are now discussing.

These are some of the more important of the earlier attempts to discover connections and relations between the different chemical elements. None of these, with the exception of the hypothesis of Prout, can be said to have attempted to solve the problem of the nature of the chemical elements, even as referred to some one known element as the standard.

In the above very brief review of the efforts that have been made to establish connections between the various chemical elements, a number of pure speculations by the ancients have been omitted. Most of these are only of historical interest, and since they do not admit of experimental test, are of little or no scientific importance.

We shall turn now to the electron theory of matter, and study some of its applications.

CHAPTER IV

The Nature of the Atom in Terms of the Electron Theory

According to the theory that we have just developed, all atoms of whatsoever kind are made up of electrons, which are nothing but negative charges of electricity in rapid motion. In accepting this wonderfully simple and beautiful theory that the nature of all matter is essentially the same, we must not forget the facts of chemistry and physics which have to be accounted for. We must remember that we have over seventy apparently different forms of matter, which cannot be decomposed into anything simpler, or into one another, by any agent known to man. We must also remember that these elements of the chemist have each their definite and distinctive properties, both physical and chemical. They enter into combination with one another in perfectly distinctive ways, and form compounds with definite and characteristic properties. In a word, we must remember the almost unlimited facts of chemical science, which are facts, regardless of whatever conception of the ultimate nature of matter we may hold.

We must also not be unmindful of the great mass of facts that have been brought to light as the result of the application of physical forces to these apparently different kinds of matter. To take one concrete example: The results of spectrum analysis show that most of the chemical elements have their own definite and characteristic spectrum.

That an element sets up vibrations in the ether that are of perfectly definite wave-lengths, and by means of which the element in question can be identified — these being different for every element.

Further, while this is true, certain simple and beautiful relations between the wave-lengths of the waves sent out by a given element have been discovered.

Thousands of facts of the character of those mentioned above must be dealt with by any ultimate theory of matter that can be regarded as tenable.

The atomic masses of the chemical atoms are as different as 1.01 for hydrogen and 238.5 for uranium, and all intermediate orders of magnitude are met with. These masses are due to the electrical charges or electrons of which the atoms of all the elements are composed.

We might at first thought conclude that the atom of one element differs from the atom of another element *only in the number* of electrons contained in it, and that the atoms are simply condensed groups or nuclei of electrons.

Such a conception would be at variance with the facts of both chemistry and physics. In terms of such a conception, how could we account for chemical valency, the acid-forming property of some elements and the base-forming property of others? In terms of such a condensation conception of the electrons, how should we account for the facts of spectrum analysis?

It was recognized by J. J. Thomson, to whom we owe the entire electron conception, that we cannot do so.

It is true that the atoms with different atomic masses must have different numbers of electrons in them. While this is a necessary condition, it is far from sufficient to account for the facts of either chemistry or physics.

THOMSON'S CONCEPTION OF THE ATOM

The electrons are moving with high velocities in orbits within the atom, occupying a relatively small part of the volume occupied by the atom as a whole. The spaces between the electrons in an atom are relatively enormous, compared with the spaces occupied by the electrons themselves. But the electrons are negative electrical charges, and we cannot have negative electricity without the corresponding positive. Where is the positive electricity corresponding to these negative units?

Thomson[1] supposes the atom to be made up of a sphere of uniform positive electrification, through which the electrons or negative charges are distributed. These electrons are, as we have seen, at enormous distances apart compared with the spaces actually occupied by them, like the planets in the Solar System; and move with very high velocities. The corpuscles are so distributed through the positive sphere as to be in dynamical equilibrium under the forces that are acting upon them. These are the attraction of the positive electricity for the negative electrons, and the repulsion of one negative electron by another.

This brings us to an extremely interesting development of the electron theory. J. J. Thomson has solved the problem, in part, as to the arrangement of the corpuscles that will produce stable systems, in the case of a number of the less complex atoms.

THE ELECTRON THEORY AND THE PERIODIC SYSTEM

Thomson has calculated the arrangement of the electrons in a sphere of positive electrification, which will be stable. The electrons will arrange themselves in concentric rings,

since a large number of corpuscles arranged in a single ring cannot be stable. This ring, however, will become stable when a suitable number of corpuscles are placed in the interior, which would produce a system with concentric rings.

In the following table is given the total numbers of electrons, in which the outer ring will contain twenty, and also the numbers that will be contained in the inner rings, which are four in number.

NUMBER OF ELECTRONS

59	60	61	62	63	64	65	66	67

NUMBER OF ELECTRONS IN EACH RING

2	3	3	3	3	4	4	5	5
8	8	9	9	10	10	10	10	10
13	13	13	13	13	13	14	14	15
16	16	16	17	17	17	17	17	17
20	20	20	20	20	20	20	20	20

The smallest number of electrons which will have an outer ring of 20 is 59, and the largest number with an outer ring of 20 is 67. When the total number is less than 59, the outer ring will contain less than 20, which would necessitate a rearrangement of the corpuscles. If an electron was removed from such a system, the system would of necessity be broken down, and the electrons rearranged in a new form, which would be the stable form for 58 electrons. It we pass to the other extreme of the systems containing 20 electrons in the outer ring, we shall find exactly the reverse condition. We cannot add an electron to this system without destroying the equilibrium. If an electron were added, there would be an entire rearrangement of the whole system, giving us a new system with 21 electrons in the

outer ring. This complete breaking up of the system would, of course, be a difficult matter.

Turning now to the systems containing total numbers of electrons intermediate between 59 and 67, some unusually interesting relations manifest themselves. Take the system with 60 electrons. *One electron, and only one, can be detached from this system* without destroying the equilibrium and necessitating a rearrangement of the remainder. The removal of one electron reduces the total number to 59, which, as we have seen, is the smallest number that is stable with 20 in the outer ring. Such a system having lost one electron, which is one unit of negative electricity, would be *electropositive*.

The recent study of chemical valency from the standpoint of modern physical chemistry has shown that Faraday's law is the basis of all chemical valency. This means that a univalent element is one that carries unit electrical charge, a bivalent element two such charges, and so on. In the light of these facts we see that the above system with 60 corpuscles, having lost one electron, or one negative charge, would contain *one positive charge in excess*, and would, therefore, be a *univalent positive element*, while the system with 59 corpuscles would have no valency.

The system containing 61 electrons could lose two without destroying the equilibrium, and would, therefore, be a *divalent, positive element*.

The system with 62 electrons could lose three without destroying the equilibrium, and would correspond to a *trivalent, positive element*.

If now we pass to the system with 63 electrons, we can *add four electrons* without increasing the total number beyond 67, and, therefore, without destroying the stability of the system as a whole and necessitating a rearrangement.

Such a system would correspond to a *tetravalent negative element*.

Similarly, three electrons could be added to the system where the total number is 64, two to the system containing 65, and one to the system containing 66, without destroying the equilibrium. These would then correspond respectively to *trivalent*, *bivalent*, and *univalent electronegative* elements.

When we come to the system with 67 electrons, we find conditions that suggest those pointed out with the system with 59 electrons. Just as in the latter case we cannot remove an electron without destroying the equilibrium, just so when we have 67 electrons we cannot add an electron without destroying the equilibrium and necessitating a rearrangement of the system as a whole; since, it will be remembered, that 67 is the largest total number of electrons that can have an outer ring of 20. This, like the system with 59 electrons, would correspond to an element with no chemical valency.

Turning now to the Periodic System, we find, as Thomson pointed out, that the first nine elements are the following: Helium, lithium, glucinum, boron, carbon, nitrogen, oxygen, fluorine, and neon.

The second series of nine elements is the following: Neon, sodium, magnesium, aluminium, silicon, phosphorus, sulphur, chlorine, and argon.

It will be recognized that the first and last member of each of the above series has no valency, since they have not been made to combine chemically with anything else. Lithium and sodium are univalent elements and electropositive, glucinum and magnesium are bivalent and electropositive, boron and aluminium are trivalent and electropositive, carbon and silicon are tetravalent and electronegative, nitrogen and phosphorus trivalent

and electronegative, oxygen and sulphur bivalent and electronegative, fluorine and chlorine univalent and electronegative, while neon and argon have no chemical valency — having never been made to combine with any other element. A more perfect agreement, as far as it goes, between the deductions from any theory and the facts could not exist. ✗

Relations such as the above, which have been pointed out by Thomson, have done much to bring the electron theory of matter to the front, and are altogether too comprehensive to be attributed to accident. This application of the electron theory to the Periodic System is one of the most important applications of this conception that has thus far been made.

THE ATOM IN TERMS OF THE ELECTRON THEORY

The *atom* according to this theory is *very complex*. Take, for example, the atom of mercury. This contains somewhat more than 150,000 electrons, and some of the heavier atoms are even more complex. The approximate number of electrons contained in an atom is found by multiplying the atomic weight of the atom in terms of hydrogen as the unit, by 770.

This complex nature of the atoms enables us to account for the facts of spectrum analysis. Certain elements, such as iron, uranium, etc., give out thousands of wave-lengths in the ether, in accordance with the prevailing theory of light; as is shown by the enormous number of spectrum lines produced by these elements. In terms of the old conception of the atom, it was difficult to see how such a large number of vibrations of such widely different periods could be set up in the ether by a single element. Before we had the electron theory, it was recognized that the atom must

in its ultimate essence be complex, in order to produce such effects as are brought out by spectrum analysis alone. The writer has heard Rowland frequently say, that the simplest atom must be more complex than a piano.

The electron theory, giving us some idea of the complexity of even the simplest atoms, makes it possible to form a mental picture of how an atom can produce such effects in the ether as is shown by a study of the spectrum.

Light is not only thrown, by the electron theory, on the problem of spectrum analysis, but on a host of similar problems, which it would lead us too far in this connection to discuss.

CATIONS AND ANIONS IN TERMS OF THE ELECTRON THEORY

When acids, bases, and salts are dissolved in water they break down into a positively charged constituent known as a *cation*, and a negatively charged constituent known as an *anion*. The recognition of this fact is one of the most important contributions to scientific knowledge made by modern physical chemistry. Before we had the electron theory, we could not form any very definite mechanical conception of how this important process takes place.

We knew that all acids yielded the hydrogen cation, which gave their solutions acid properties, and that the remainder of the molecule, as a whole, was charged negatively and formed the anion of the acid.

We also knew that bases dissociated in the presence of a dissociating solvent, yielding the hydroxyl anion which was characteristic of all bases, and to which the basic properties are due; and that the remainder of the molecule of the base became charged positively, and formed the cation of the base. Just as all acids yield the hydrogen cation, so all bases yield the hydroxyl anion.

We knew, further, that salts in the presence of a dissociating solvent, break down or dissociate, as we say, into a cation and an anion — the cation being the cation of the base from which they were formed, and the anion the anion of the acid which took part in the formation of the salt.

We were, however, not able to form any definite conception of how certain atoms or groups (usually atoms) became charged positively and thus became cations, or how certain other atoms or groups (usually groups of atoms) became charged negatively and thus became anions.

The electron theory solves this problem in a very satisfactory manner. When an atom *loses an electron* it becomes charged *positively*, since the loss of a negative charge is exactly equivalent to gaining a positive charge. Thus, *a cation is an atom or group of atoms that has lost an electron.*

If an atom takes on an electron it becomes charged negatively. *An anion is then an atom or a group of atoms that has gained an electron.*

A bivalent cation is one that has lost two electrons, a trivalent cation is one that has lost three electrons, and so on.

A bivalent anion is one that has gained two electrons, a trivalent, one that has gained three electrons, and so on for the polyvalent anions.

Since a great majority, if not all chemical reactions take place between ions, and since electrons are so vitally connected with the formation of ions, it follows that the electron theory is of as much importance for the science of chemistry as for the science of physics.

THE MASS OF AN ION NOT EXACTLY THE SAME AS THAT OF THE ATOM FROM WHICH IT IS FORMED

From the above method of ion formation, it is obvious that the mass of an ion is *different* from that of the atom or

group of atoms from which it was formed. Since a cation is an atom, or group of atoms, from which one or more electrons have been split off, a *cation has a smaller mass than the atom or atoms from which it was produced.*

An anion, on the other hand, is formed from an atom or group of atoms by *adding* one or more electrons. Therefore, the *mass of an anion is greater than the mass of the atom or atoms from which it was produced.*

It must, however, be remembered that the difference between the mass of an atom or group of atoms, and the corresponding ion, is in any case very small. Take the hydrogen atom and the hydrogen ion, where the difference is the greatest. The hydrogen atom contains about 770 electrons. The loss of an electron, converting the hydrogen atom into the hydrogen cation, would change the mass only about $\frac{1}{770}$. This is close to the limit of accuracy of our most refined methods of measuring mass, and it is, therefore, doubtful whether we could detect the difference between the mass of a hydrogen atom and the corresponding hydrogen ion even when a large number were employed. It would, however, be rash to assert that such differences would never be detected, or even determined, by using a very large number of hydrogen atoms and comparing them with the corresponding ions.

The change in mass would be *relatively less* for any other atom when it is converted into the corresponding ion, since the mass of any other atom is so much greater than that of the hydrogen atom, and the absolute gain or loss in mass would be the same for any other univalent ion, as for hydrogen — a loss for every cation, and a gain for every anion. That this is true is seen from the fact that every univalent ion differs in mass from the corresponding atom only in containing *one more* or *one less electron.*

The same remark holds for polyvalent ions, which differ from the corresponding atoms or groups of atoms in that they contain a number of electrons greater or less than the corresponding atoms, expressed by the valency of the ion in question. The mass of all such ions is, however, so much greater than that of the hydrogen ion, that if we divide their mass by their valency, the result is still many times greater than the mass of the hydrogen ion. The greatest change in mass is, therefore, that produced when a hydrogen atom loses an electron and passes over into the hydrogen ion.

Whether or not this *change in mass* can ever be detected directly, it is important to recognize that the *mass does change* whenever an atom or group of atoms passes over into ions. There is a gain in the mass of an atom whenever an anion is formed from it, and a loss in the mass of an atom whenever a cation is formed.

It must, of course, be remembered that a cation is never formed without the corresponding anion being formed, and *vice versa*; so that in ionization the anion gains just as much in mass as the cation loses, and *the total mass consequently remains unchanged.*

When a molecule of an electrolyte, say sodium chloride, breaks down into ions, what takes place is the transference of an electron from the sodium, which becomes a cation, to the chlorine, which becomes an anion. The sodium loses in mass an amount equal to the mass of an electron, and the chlorine gains the same amount in mass; the sum of the masses of sodium and chlorine remaining constant.

There would be a change in the total masses in ionization only if we assumed that there was a change in the velocities of the electrons in the sodium and in the chlorine, when ionization takes place, and that these changes in the

velocities did not exactly compensate one another. Since there is, at present, no ground for such an assumption, we must conclude that the *total masses* of the ions formed from any molecule are *equal to the mass of the molecule.*

THE ELECTRON THEORY AND RADIOACTIVITY

One of the most important bearings of the whole electron theory of Thomson is in connection with those investigations on *radioactivity* which have recently attracted so much attention; investigations which have opened up an entirely new branch of experimental physics, and which have changed some of our fundamental conceptions.

The application of the electron theory to these epoch-making investigations will be made when these researches are studied. The importance of this theory in connection with radioactivity is one of the reasons why the theory has been discussed at some length at the beginning of this work. Another reason, if other reasons were needed, is its own inherent importance and interest in connection with physics, physical chemistry, and chemistry, not to say in connection with all branches of natural science.

CHAPTER V

THE X-RAYS

IN 1895,[1] a paper appeared by Röntgen, then of Würzburg, now of Munich, "On a New Kind of Radiation." It was announced that when an electric discharge is passed through a Crookes or Lenard tube, which is nothing but a high-vacuum tube, there was given off from the tube a kind of radiation which was unknown up to that time, and which has most remarkable properties. Among these was the property of *great penetrability*. The radiation passed through objects which were entirely opaque to light, and affected a photographic plate. When a photographic plate was covered with perfectly black paper, or placed in a black wooden box, through which no light could pass, the plate was still affected by the newly discovered radiation. Indeed, it was this fact that led to the discovery of the radiation by Röntgen.

It was found that the radiation could pass through a great number of objects that were entirely opaque to light. Thus, comparatively thick sheets of some of the metals, such as aluminium, were quite transparent to the newly discovered radiation. It had the power of passing through metals in general; but the heavy metals, such as lead, platinum, and the like, were much more opaque to the radiation than the lighter metals. It was soon found that the bones of the body are far more opaque to the radia-

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[1] Wied. Ann., **64,** 1 (1898).

tion than the flesh, and, therefore, photographs of the living skeleton could be obtained, which led to a large amount of dilettanteism. It was announced that the radiation could not be refracted, nor polarized. When passed through a gas it rendered the gas a conductor, or, as we have seen, ionized the gas, in part.

Of course, these were at once recognized to be very remarkable properties; many of them entirely different from those of any known form of radiation. In some respects it resembled light, but in most of its properties differed fundamentally from it.

It is but natural that such a discovery should have awakened the broadest and deepest interest on the part of men of science, the world over, almost regardless of the branch of natural science to which they were devoting their energies. The first question that would naturally be asked was, *What is this newly discovered kind of radiation?* In answering this question the method of producing the radiation must be carefully taken into consideration.

NATURE OF THE X-RAY

It will be seen that the X-ray is produced in the ordinary cathode discharge tube, and this alone would serve to connect this portion of the work with what has preceded. We have already studied the cathode discharge, and the velocity and nature of the cathode particle. We now see that a remarkable kind of radiation is given off from the cathode tube.

Careful study showed a very close connection between the cathode discharge and the production of the radiation. It was found that the X-rays were produced where the cathode rays strike upon a solid body, such as the glass walls of the low-pressure tube. The cathode rays are thus vitally connected with the production of the X-rays.

Several theories have been advanced to account for the nature of the new radiation. While in a few respects it resembled light, in most of its properties it differed fundamentally from light. Light is a *transverse* vibration of the ether, the X-ray might be a *longitudinal* vibration in the ether, and this was the theory that was proposed by Röntgen to account for the radiation that he had discovered. As facts accumulated, this theory was found to be insufficient. Indeed, it never acquired any prominence, or received any very serious support. It remained for Sir George Stokes to propose a theory as to the nature of the X-ray that would prove to be satisfactory, and account for the facts then known, as well as for those subsequently to be discovered.

The X-ray is not a succession of waves in the ether, like light, but a *series of pulses in the ether, sent out at irregular intervals.* This was in accord with their mode of formation, and accounted for their properties. They are produced when the cathode particles in a cathode discharge fall upon the glass walls of the confining vessel. These particles rain down upon the walls of the tube at irregular intervals, and if they set up any vibration in the ether, it would be expected that it would be irregular in character.

Further, matter would be supposed to be far *more transparent* to such a set of irregular pulses, than to a definite, regular set of vibrations in the ether, such as corresponds to a wave of light. To say that an object is transparent to any given form of radiation, means that it is not thrown into vibration by the radiation when the radiation falls upon it. On the other hand, to say that an object is opaque to a vibration, means that it is thrown into vibration by the radiation. Glass is transparent to light because it is not thrown into vibration by the light. A thin sheet of metal

is opaque to light because the light waves falling upon it produce vibrations within the metal.

This is just what we should expect, since, if the radiation sets up vibrations in the object upon which it impinges, its energy is expended in setting up the vibrations, and the radiation as such is lost.

The penetrating power of the X-ray is thus explained by the Stokes theory as to its nature.

Similarly, this theory accounts satisfactorily for the other well-recognized properties of the X-ray, and is now generally accepted.

THE BECQUEREL RAY

The X-ray is produced, as we have seen, where the cathode ray falls upon the wall of the glass tube. It will be remembered, that where the cathode ray falls upon the wall of the tube a phosphorescent spot is produced on the glass. For a time it was supposed that this phosphorescence is in some way intimately connected with the production of the X-ray. Although it has subsequently been shown that this is not the case, and that X-rays are produced better when the cathode ray falls upon a metal plate which does not become phosphorescent, than when it falls upon glass which does; yet this original idea, although erroneous, led to highly important discoveries.

With the idea that phosphorescence and X-rays are vitally connected, men of science began to examine bodies that were naturally phosphorescent, to see whether they gave off any form of radiation analogous to the X-ray, or any unknown form of radiation whatsoever.

It remained for Henri Becquerel[1] to *discover the first naturally radioactive substance.* Guided by the erroneous

[1] Compt. rend., **122**, 501, 689, and 762 (1896).

idea that there was some connection between the phosphorescence produced on the glass by the cathode ray, and the production of the X-ray by cathode rays, Becquerel began examining phosphorescent substances to see if any of them gave off a radiation at all analogous to the X-ray. He chose among these substances the salts of uranium, and found that these compounds produced an impression on a photographic plate wrapped in black paper to cut off all ordinary light. The radiations given off by the salts of uranium could pass through thin sheets of metal and still affect the photographic plate.

Becquerel supposed at first that it was necessary to expose the phosphorescent salts of uranium to sunlight, in order to obtain from them the radiation referred to above. He found later that this radiation was given off even when the uranium compound had not previously been exposed to light.

Becquerel tested the question, as to whether the effect on the photographic plate was due to any volatile substance given off from the uranium salts. This was especially desirable in the light of the recent work of Russell, on substances that would produce a fogging of photographic plates, even when the plate was not directly, but only indirectly, exposed to the substances in question. To test this point the photographic plate, wrapped in black paper, was screened from the uranium compound by a thin plate of glass. The glass would have cut off any volatile substance given off from the compound of uranium. The photographic plate was still affected, which showed that the result was not due to any volatile substance coming from the salt of uranium.

Becquerel found that *all the salts of uranium* would pro-
the effect, both those that are phosphorescent, and

those that are not. The phenomenon was thus shown not to be directly connected in any way with phosphorescence. The effect produced by the non-phosphorescent compounds was just as great as that produced by those that are phosphorescent, provided that they were taken in quantities that contained the same amount of uranium. The phenomenon was therefore due to the uranium itself. It was soon shown that metallic uranium was not only active, but more active than any of its compounds.

The radiations given off by uranium, either in the elementary state or in its compounds, have nothing to do with its previous exposure to light. When the metal or its compounds are kept for a long time in the dark, the intensity of the radiation is undiminished. It is thus obvious that the energy given out by the uranium radiations is not derived from sunlight.

Further, the intensity of the radiation given out by uranium is not diminished in several years, *i.e.*, during the longest time over which observations have thus far been extended. In these experiments the uranium salts were preserved in lead boxes, which are especially opaque to such radiations as we are now considering, and the intensity of the radiations measured photographically from time to time without removing the uranium compound from the lead box. In this way the uranium salt was never exposed to radiations from external sources, and yet it continued to give off radiations with undiminished intensity. The energy of the uranium radiation is thus intrinsic in the uranium, and does not come from any external source.

This property of substances to emit radiations naturally like uranium, without any external cause, is known as *radioactivity*, and such substances are *radioactive*. There are a number of such instances, as we shall see.

PROPERTIES OF THE BECQUEREL RAY

It was early recognized that the uranium radiations, like the Röntgen rays, have many remarkable properties. As we shall see, they have some properties in common, while others are quite different.

The uranium radiations, like the X-ray, have the property of ionizing gases through which they pass. This is shown by the fact that they discharge electrified bodies surrounded by the gases in question. The gases are ionized by the radiations, and then conduct the charges away from the charged bodies with which they come in contact.

In this respect, as well as in their power to affect a photographic plate, the uranium rays act like the X-ray, but they are very much weaker in their action. This applies both to their action on a photographic plate, and their power to ionize a gas. From these facts alone it might be concluded that the Becquerel ray is nothing but a very weak form of X-ray.

The rays from uranium can neither be refracted nor polarized, and thus again resemble the X-ray.

THE THORIUM RADIATION

After Becquerel had shown that one natural substance is radioactive, or has the power of giving out radiations that can pass through considerable thicknesses of matter opaque to light, as well as ionize a gas and affect a photographic plate, a search was made for other natural substances having the same properties. The first one discovered was the comparatively rare element thorium. Schmidt[1] found that thorium, whether elementary or in combination, had some properties analogous to those possessed by uranium. It gave out radiations that acted, if only feebly, upon the

[1] Wied. Ann., **65**, 141 (1898).

photographic plate. It ionized a gas, like the radiations from uranium, but possessed properties that distinguished it sharply from the uranium radiation. There is given off from the thorium something that is blown about by the slightest currents of air, and which in some respects resembles a gas. This was discovered by Rutherford and termed by him an *emanation*. As we shall learn, this emanation has remarkable properties.

CHAPTER VI

THE DISCOVERY OF RADIUM

It having now been shown that two elementary substances, uranium and thorium, are radioactive, a large number of substances were examined with respect to this property. Among these would naturally be the minerals in which uranium and thorium occur.

Mme. Curie[1] determined the radioactivity of a large number of minerals, by measuring the conductivity of the air when exposed to these substances. She found that all minerals which show radioactivity contain either uranium or thorium. What was very remarkable was the fact that *certain minerals which contain many things in addition to uranium were much more radioactive than uranium itself.* Thus, pitchblende from Johanngeorgenstadt had nearly four times the radioactivity of pure uranium. Pitchblende from Joachimsthal was three times as radioactive as uranium, while pitchblende from Pzibran was nearly three times as radioactive.

Chalcolite, which is a double phosphate of copper and uranium, is about two and one-fourth times as radioactive as metallic uranium, while autunite, a double phosphate of calcium and uranium, is about one and one-fifth times as radioactive as uranium.

Only a part of every one of these minerals is uranium, and yet the mineral was more radioactive than pure uranium itself.

Mme. Curie then prepared chalcolite artificially by treat-

[1] Ann. Chim. Phys. [7], **30**, 99 (1903).

ing a solution of uranyl nitrate with a solution of copper phosphate in phosphoric acid, and warming the mixture to fifty or sixty degrees. Under these conditions crystals of chalcolite were formed.

The radioactivity of this artificially prepared chalcolite was two and one-half times *smaller* than that of uranium itself. This led Mme. Curie to conclude that the unexpectedly great activity of the natural minerals was due to the *presence in them of small quantities of some strongly radioactive substance*, which was neither uranium, nor thorium, nor any other known substance.

With this idea in mind M. and Mme. Curie undertook to separate from the uranium minerals the supposed new radioactive substance, and with signal success.

THE SEPARATION OF RADIUM FROM PITCHBLENDE

Pitchblende, as is well known, contains, in addition to uranium, a large number of other elements in small quantities. The separation of pitchblende into its constituents, or even the separation of any constituent in pure form, is not likely to be a simple matter. The Curies, however, worked out a chemical method for effecting the desired separation, and obtaining the highly radioactive substance or substances.

In the various chemical processes to which the material, as we shall see, was subjected, they followed the course of the radioactive constituents by determining the radioactivity of every product by means of the electroscope. They could thus determine what chemical operation was concentrating the radioactive substance.

There are at least two, and possibly three radioactive constituents in pitchblende, in addition to uranium itself. One of these, called *polonium* from the native country (Poland) of Mme. Curie, resembles in its chemical proper-

ties the element bismuth, and is separated from the pitch-blende along with this element. The element radium, with which we are now chiefly concerned, is closely allied chemically to barium, and comes out of the pitchblende along with the barium.

A third radioactive substance, *actinium*, has been described by Debiern as occurring in pitchblende. It seems to separate from pitchblende along with certain of the rare elements, and especially thorium.

To give some idea of the number and complexity of the chemical processes involved in separating radium from pitchblende, the essential features in Mme. Curie's [1] account of her own work are appended. All of the new radioactive constituents occur in pitchblende in *minute quantities*, so that it is necessary to work over enormous quantities of material in order to obtain even a few milligrams of the comparatively pure radioactive substances.

We shall confine our account to the separation of radium from pitchblende, which, we will remember, comes out along with the barium, to which it is so closely related chemically.

The finely powdered pitchblende is fused with sodium carbonate, and the product treated with hot water. Dilute sulphuric acid is then added. The uranium is contained in the solution, and since the pitchblende was worked for the uranium that it contained, the residue, after the above treatment, was discarded. The radioactive constituents are contained in this residue, which has a radioactivity of about 4.5 times that of metallic uranium.

This residue consists mainly of the sulphates of lead and calcium. It also contains aluminium, iron, silicon, and larger or smaller amounts of nearly all known metals. The

[1] Ann. Chim. Phys. [7], **30**, 125–127.

radium exists in this mixture of sulphates, its sulphate being the least soluble.

The problem now is to separate the radium from this mixture of sulphates. The residue is freed as far as possible from sulphuric acid, by treating with a concentrated, boiling solution of sodium hydroxide. The sulphates of calcium, aluminium, and lead are thus, for the most part, decomposed, the sodium hydroxide also removing the aluminium, silicon, and lead. The residue insoluble in the alkali is washed with water and then treated with hydrochloric acid. The radium remains in the residue insoluble in hydrochloric acid.

The insoluble portion containing the radium is washed with water, and then treated with a concentrated, boiling solution of sodium carbonate. This transforms the sulphates of barium and radium into carbonates. The carbonates are now thoroughly washed with water and treated with hydrochloric acid, when the barium and radium dissolve as the corresponding chlorides. The radium is precipitated by means of sulphuric acid. The precipitate also contains barium and calcium, lead and iron. *This is the radium-containing barium in the form of crude sulphate.*

From a ton of the residue obtained from pitchblende, ten or twenty kilograms of the crude sulphate, having an activity from thirty to sixty times that of metallic uranium, which is taken as unity, can be obtained.

The mixture of crude sulphates is boiled with a solution of sodium carbonate, and then transformed into chlorides by treating the carbonates with hydrochloric acid. The oxides and hydroxides are precipitated by adding ammonia after filtering. Sodium carbonate is added to the solution, when the carbonates of the alkaline earths are thrown down. The carbonates are transformed into chlorides by adding hydrochloric acid, and the chlorides, after evaporating the so-

lution to dryness, are treated with pure, concentrated hydrochloric acid. This dissolves the chloride of calcium, while the chlorides of barium and radium are insoluble in the acid.

About eight kilograms of this product, consisting mostly of barium chloride, are obtained from a ton of the original residue. The radium chloride is mixed in small quantity with the barium chloride. This is shown by the fact that the activity of the radium-bearing chloride is about sixty times that of pure uranium.

The process of preparing pure radium chloride, instead of being ended, is now really only begun. The following process of obtaining radium chloride from the mixture with barium chloride is described by Mme. Curie.[1]

The principle of the method is *fractional crystallization*. The chloride of radium is less soluble than the chloride of barium.

The first fractionation is effected in pure water. The chloride that separates from the saturated solution is much more active than the solution, as would be expected, since the chloride of radium is less soluble than the chloride of barium. By utilizing this fact, and fractionating the mixture in terms of it, after a long series of fractionations, discarding the weakly active portions, most of the inactive barium chloride is removed.

When a large number of fractionations have been made, and the amount of substance has become small, it is better to add hydrochloric acid to the water, since this diminishes the solubility of the salts, and more rapid separations are effected.

Mme. Curie observed that the crystals of radium barium chloride remain colorless, until the amount of radium has reached a certain per cent. of the whole mass. When the radium salt has reached a certain concentration, the crys-

[1] Ann. Chim. Phys. [7], **30,** 131 (1903).

tals become yellow. They may even show an orange, or a beautiful rose color. This color possessed by the crystals disappears when the crystals are dissolved. The appearance of this color is rather remarkable, since crystals of pure radium chloride are colorless. The color indicates that a certain degree of purity has been reached, and has a maximum intensity when the amount of radium present is a certain, definite quantity. After this concentration is reached, the intensity of the color becomes less and less as the purity of the crystals becomes greater and greater. When the radium has become freed from all appreciable quantities of barium, the color practically disappears from the crystals. Thus, the color of the crystals can be used as an index to the progress of the separation of barium from the radium — of the degree of purity of the radium salt. For a more detailed discussion of these matters see the original article by Mme. Curie.

By the above described method radium chloride can be obtained, having a radioactivity that is *one million times that of the mineral from which it came.*

When we consider the number of steps in the above described process, and the details of every step, and then remember that every one of these details had to be worked out empirically by the Curies, we gain some idea of the enormous task that they have performed, and the difficulties at every step which they must have encountered and have overcome.

After all this had been done, the amount of radium chloride obtained from a ton of the residues from pitchblende was only a *few milligrams.* This necessitated the working over of enormous quantities of the original pitchblende, in order to obtain any appreciable quantity of the radium salt. Fortunately, this problem is rendered much less difficult

than it would otherwise be, by the coöperation on the part of the factories in which pitchblende is used. Many of the steps described in the above process can be taken *more successfully* on a large scale than on a small one, to say nothing of the amount of time and labor that it would be necessary to expend in performing these operations in the laboratory.   Indeed, if we were dependent upon the laboratory alone for our supply of radium, our knowledge of this substance would have accumulated infinitely more slowly than it has done.

Other methods have been proposed for purifying the radium salt, which are hardly more than modifications of certain details of the method worked out by the Curies and described above.

The question that arises is whether some source of radium richer than pitchblende may not yet be found. Radium has been shown to be very widely distributed over the surface of the earth. It occurs in a large number of minerals, in the waters of many springs, in the soil and rocks, and probably in many places not yet discovered. While sources of radium that are richer in this substance than the richest pitchblendes may yet be found, it appears to the writer to be doubtful whether any material very rich in radium will ever be found.

This opinion is not based so much upon the ease with which radium is detected by means of the electroscope, or upon the comparatively wide search that has already been made for this substance, as it is upon the *instability of the element itself*.

As we shall see, radium is not a stable substance. It is continually undergoing decomposition into other things. It would, therefore, be very surprising if any large quantity of it should be found in any one locality.

THE SPECTRUM OF RADIUM

Since radium has a well-defined spectrum, it is a matter of great importance in connection with the determination of the purity of any given sample of its salts. To determine the spectrum, the Curies[1] turned over to Demarçay some samples of material containing radium, and he studied the spark spectra of these substances. The first sample used by Demarçay contained large quantities of barium. Nevertheless, even with this material he was able to recognize, in addition to the barium lines, a line in the ultraviolet, having a wave length of 3814.7 Ångström units. When a purer substance was used the intensity of this line increased, and other lines made their appearance. Finally, a product was obtained of such purity that only the three strongest barium lines appeared at all, and these were of such slight intensity as to show that the barium was present only in very small quantity. While this product was nearly pure radium chloride, it was still further purified until the strongest barium lines could scarcely be detected at all.

The chief lines of radium found by Demarçay, lying between 5,000 and 3,500, are the following — the most intense line being represented by the number 16.

Wave Length	Intensity
4826.3	10
4683.0	14
4533.5	9
4436.1	8
4340.6	12
3814.7	16
3649.6	12

[1] Ann. Chim. Phys. [7], **30**, 121 (1903).

The strongest of the above lines have the intensity of the stronger lines of other substances.

In addition to the lines referred to above, and a number of weaker lines, the spectrum of radium contains two bands; the one extending from 4631.0 to 4621.9, the other a stronger band in the ultraviolet, extending from 4463.7 to 4453.4.

Thus, the spectrum of radium resembles the spectra of the alkaline earths, which consist of strong lines and also bands.

It was pointed out by Mme. Curie that although spectrum analysis is, in general, a very sensitive means of detecting minute quantities of substances, in the case of radium it is far less delicate than the electrometer, notwithstanding the fact that radium gives a well-defined spectrum.

In order to photograph the strongest spectrum lines of radium, a specimen of the radium-containing barium was required, which had an activity at least fifty times that of metallic uranium.

A very sensitive electrometer, on the other hand, can detect radium which has an activity that is only one ten-thousandth that of metallic uranium. The electrical method of detecting the presence of traces of radium is thus at least *five hundred thousand times more sensitive than the spectroscopic*. The spectroscopic method is of importance in connection with the study of radioactivity, not so much as a method for measuring radioactivity, as for determining the purity of the radium in the various stages of its separation from barium. Radium bromide gives a deep-red color to the flame.

THE ATOMIC WEIGHT OF RADIUM

The atomic weight of radium was first determined by Mme. Curie,[1] with specimens that contained more or less

[1] Ann. Chim. Phys. [7], **30**, 137 (1903).

barium. Values as low as 140 were at first obtained. As purer and purer specimens were prepared, successive determinations gave larger and larger values for the atomic weight of radium.

A specimen which still showed the strongest lines of barium with appreciable intensity, gave a value for the atomic weight of radium ranging, for five determinations, between 220.7 and 223.1.

A specimen of radium chloride was then purified until the strongest lines of barium appeared very weak indeed. From the minute quantity of barium that can be detected by the spectroscope, this specimen of radium chloride could contain only the merest trace of barium.

The atomic weight determinations were made by precipitating the chlorine as silver chloride. Taking the atomic weight of silver as 107.8 and chlorine as 35.4, the atomic weight of radium was found to be 225, ranging in three determinations between 224.0 and 225.8.

Light has been thrown on the atomic weight of radium by Runge and Precht,[1] who studied the spectrum of radium in a magnetic field. Series of lines were observed, with radium, under these conditions, that are analogous to those found for the alkaline earth metals — calcium, strontium, and barium. Certain relations have been established between the series of lines for an element, and its atomic weight. By means of these relations Runge and Precht have calculated the atomic weight of radium to be 257.8. However, other investigators, and especially Watts, on purely physical grounds, have concluded that the atomic weight is close to 225. We must, then, decide between these two numbers. In the light of the evidence at present available, this is not an easy task.

[1] Phil. Mag., **5,** 476 (1903).

The number 225 seems to fall in with the value that radium might be expected to have from the Periodic System. This number would place radium after bismuth with an atomic weight of 208.5 and before thorium with an atomic weight of 232.5 The number 225 for its atomic weight would place radium in group II, along with calcium, strontium, and barium, to which chemically it is closely allied — especially to barium, as we have seen. The atomic weight 225 also places it in the twelfth series, along with thorium and uranium — the other well-known elements that are radioactive.

On the other hand, the atomic weight 225 places radium in the second group of the Periodic System, while thorium is in the fourth, and uranium is in the sixth. In a word, it places radium *before* thorium and uranium; the atomic weight of thorium being 232.5, and that of uranium 238.5. It will be observed that these three radioactive elements have the *largest atomic weights of all the known chemical elements*. Indeed, an attempt has been made to establish a relation between the relatively large masses of the atoms of these elements and their radioactivity — an attempt which, as we shall see when we come to study the nature of radioactivity, is most praiseworthy. In terms of this relation, the atom with the largest mass should be the most radioactive, and as we usually measure mass by weight, the atom with the largest atomic weight should be the most radioactive. If the atomic weight of radium is 257.8, it would be in accord with this relation. The atom of radium would be by far the *heaviest* of all known atoms, that of uranium with a mass of 238.5 would be next, followed by thorium with a mass of 232.5.

We shall see later the significance of this relation, and will become so impressed by it in connection with the appli-

cation of the electron theory of matter to the explanation of radioactivity, that we shall be loath to give it up, and accept a lower atomic weight for radium than for uranium and thorium.

Since writing the above a relation has appeared to the writer,[1] which somewhat invalidates the argument for 225 as the atomic weight of radium, based upon the Periodic System. If we turn to the Periodic System and examine the atomic weights of any two elements in the same group and in two succeeding series; in a word, of two elements that fall directly under one another, we find that their atomic weights differ from one another by from *twenty-five to thirty* units. This is especially true for the elements with higher atomic weights. Take the members of group II, in which radium undoubtedly belongs chemically. The atomic weight of calcium is 40.1, that of zinc 65.4 — difference 25.3. Zinc differs from strontium in round numbers by twenty-two points; strontium from cadmium by twenty-five points, and cadmium from barium by twenty-five points. Yttrium differs from indium by twenty-six units; indium differs from lanthanum by twenty-four units; lanthanum differs from ytterbium by thirty-four units, and ytterbium differs from thallium by thirty-one units. Similar relations exist between successive members of every other group in the Periodic System, especially between the members with the higher atomic weights.

It will be seen that the difference between the atomic weight of radium as determined by chemical analysis (225), and as determined by spectrum analysis (257.8), is about thirty-three units.

We have already seen that the number 225 places radium in group II of the Periodic System, and in series twelve.

[1] Amer. Chem. Journ., **34**, 467 (1905).

The atomic weight 256 to 258 would place radium in group II of the Periodic System, and in *series thirteen*. This may seem surprising since only twelve series have thus far been recognized in the Periodic System. It may be that the proper place for radium is in a *new series*, of which only one number exists, or has, at least, thus far been discovered. If radium has an atomic weight of 258, or thereabouts, it would thus fall in group II of the Periodic System, with its chemically allied elements, just as well as if it had an atomic weight of 225. The fact that 258 places radium on the right-hand side of group II is not a serious objection to the above view, since we do not know that the relations within the groups hold for these highest atomic weights.

The problem of the atomic weight of radium, however, cannot be settled by reasoning from analogy, but must be worked out by some direct method.

If we examine the method employed by Mme. Curie for determining the atomic weight of radium, it does not seem to be entirely free from objections. In the first place, the amount of radium chloride that could be obtained, which was of sufficient purity for atomic weight determinations, was necessarily small. Indeed, the total amount of chloride at the disposal of Mme. Curie was only about one hundred milligrams. This tended to magnify all experimental errors.

The chloride of radium, which is hygroscopic, shown by the fact that it absorbs water when in a desiccator over drying agents, was weighed in a platinum crucible. Further, it is not clear that any test was made to determine whether the crystallized radium chloride did not lose hydrochloric acid when the water of crystallization was removed. It will be recalled that other members of the barium group form oxychlorides, when the chlorides are dehydrated in

the air. It is well known that the chloride of calcium can be dehydrated without the formation of oxychloride, only in a current of hydrochloric acid or by heating with ammonium chloride. This is a matter that should certainly receive attention in connection with the method of determining the atomic weight of radium, that was employed by Mme. Curie.

A further question that naturally suggests itself in connection with the method is this: Does silver nitrate precipitate all of the chlorine from radium chloride as silver chloride? The properties of radium are so remarkable, as we shall learn, that it does not follow that this would necessarily be the case. All in all, it appears to the writer that the question of the atomic weight of radium is still an open one, that can be settled only when a larger amount of material is available, and when other methods can be brought to bear on the problem.

CHAPTER VII

OTHER RADIOACTIVE SUBSTANCES IN PITCHBLENDE

POLONIUM

THERE are apparently other radioactive substances in pitchblende, in addition to radium, as we have seen. There seems to be a new radioactive substance in this mineral that is closely allied to bismuth. It has already been referred to under the name of *polonium*.[1] It is precipitated along with the bismuth, from the hydrochloric acid solution of the pitchblende residue, by means of hydrogen sulphide. It has thus far been impossible to free the supposed polonium from bismuth. Partial separation has apparently been effected, or, at least, a strongly radioactive substance has been obtained by precipitating the nitric acid solution by water. The subnitrate that is thrown down is much more radioactive than the unprecipitated portion.

It seems yet to be a question whether this radioactive bismuth really contains a new radioactive element, or is simply bismuth made radioactive by the deposition upon it of a substance coming, as we shall learn, from the radium in the pitchblende. If there is a new radioactive element associated with the bismuth, it might reasonably be expected to show definite and characteristic lines in the spectrum, as radium does. Demarçay, who worked out the spectrum of radium, was unable to find any new lines produced by the radioactive bismuth. Sir William Crookes,

[1] Ann. Chim. Phys., **30**, 119 (1903).

on the other hand, announces a new line for this substance in the ultraviolet.

If, however, it should be shown that the radioactive bismuth contains no new line, it does not prove, as Mme. Curie points out, that there is no new element contained in this substance, since there are many elements known that do not have any well-characterized spectrum. An experiment performed by Marckwald[1] in 1902 may throw some light on the nature of polonium. If a stick of bismuth is plunged into the solution of active bismuth chloride obtained from pitchblende, it becomes covered with a black coating which is extremely radioactive, and the remaining solution is no longer radioactive. This deposit is mainly tellurium, with a very small amount of the radioactive substances. An active deposit is obtained if tin chloride is added to the radioactive bismuth chloride. Marckwald thinks that this radioactive element is analogous to tellurium, and calls it *radiotellurium*. It has properties strikingly analogous to the polonium of the Curies, the analogy being especially marked between the kinds of radiations sent out by it. More work is required to show whether these substances are identical, or are different.

It should, however, be stated that the fact that polonium is precipitated from a solution of radioactive bismuth by simply introducing a piece of bismuth would alone indicate that these substances are fundamentally different. It is well known that a metal cannot precipitate more of the same metal from a solution of any of its salts. In order that a metal may be able to precipitate another from its salts, it is necessary that the metal which is thrown out of solution should have a much lower solution-tension, or stand lower in the tension series, than the metal which throws it out

[1] Ber. d. deutsch. chem. Gesell., **35**, 2285 (1902).

and takes its place. The metal which passes into solution must have the power to take the charge from the ion of the metal that is thrown out, becoming itself an ion, while the original ion is converted into an atom.

ACTINIUM

It has already been mentioned that Debierne[1] obtained from pitchblende an active substance, which he termed *actinium*. This substance is quite different from radium, and also from polonium. It comes out of pitchblende along with the rare earths, and especially with thorium, to which it is very closely allied. This is probably the same substance as that obtained from pitchblende by Giesel along with other rare elements of the cerium group. The occurrence of actinium with thorium has raised the question as to whether the apparent activity of thorium itself is not really due to the admixture of a small amount of actinium. This question can be settled, as Rutherford points out, after thorium has been obtained which is devoid of radioactivity. Since, however, it is doubtful whether this has been done, it would be premature to conclude that the radioactivity of thorium was due to the presence of small amounts of actinium. Indeed, we shall see later that it is doubtful whether this is the case — the activity of thorium probably being due to the presence of radiothorium. No spectrum has as yet been observed for actinium.

Other radioactive substances have been announced as coming from pitchblende. It is probable that these substances either contain small amounts of the other radioactive substances known to exist in pitchblende, such as radium, and probably polonium and actinium, or are made radioactive by the presence of other radioactive substances.

[1] Compt. rend. (1899), **130,** 906 (1900).

We shall learn that certain radioactive substances have the property of making other substances in contact with them radioactive.

This kind of radioactivity is known as *induced radioactivity.* We shall become more familiar with this subject when we come to study more closely, in a subsequent chapter, the nature of the radiations given off by radioactive substances.

We have now taken a brief survey of the steps involved in the discovery and isolation of the radioactive elements, and especially of the best known of them all — radium. The next step in order of logical sequence is to study the properties of these various substances, starting, perhaps, with the less active, uranium and thorium, and then taking up the more active, especially radium, about which so much and such important knowledge has already been gained.

The methods that have been employed in these investigations are not obvious, and, therefore, should be briefly considered before the results that have been obtained through their application.

THE MORE IMPORTANT METHODS USED IN STUDYING RADIO-ACTIVITY

The methods that have been employed in studying radioactivity are based, of course, upon the properties of the radiations that are given out by the various radioactive substances.

We have seen that such substances affect a photographic plate exposed to their radiations. It will be remembered that it was by means of this property that Becquerel discovered the first radioactive substance — uranium. Although this method is still used for certain purposes, there

are a number of objections to its general use in connection with the study of radioactivity. In the first place, it is not sufficiently sensitive for work with weakly radioactive substances.

Another serious objection to the photographic method is that certain radiations given off from radioactive substances, even when fairly intense, have very slight action upon the photographic plate. Another objection to the photographic method is a somewhat general one. Photographic plates are sensitive to such a number of agents. Many things when brought *in contact* with a photographic plate leave an imprint on the plate when it is developed. This can, however, be overcome by suitable precautions, and photography has proved of invaluable service in the development of scientific knowledge.

Taking all of these facts into account, the photographic method is not well adapted to the study of radioactivity in general, although it has certain special applications which are important.

Another property of radioactive substances is to cause certain substances upon which their radiations fall, to phosphoresce. This is especially true if the radiations are allowed to fall upon screens covered with the beautiful salt barium platinocyanide. The *fluoroscopic* method is of very limited applicability, since weakly radioactive substances do not produce enough phosphorescence in these screens to be observed.

We have already seen that the radiations from radioactive substances have the power to discharge charged bodies surrounded by a gas such as the atmosphere. This means that such radiations have the power to render a gas like the air a conductor of electricity. In a word, to ionize the gas into e negative electron and the relatively large positive ion.

A method based upon this property of the radiations has proved of the greatest service in connection with the study of radioactivity. Indeed, it is the only method that is capable of giving reliable quantitative measurements.

For details concerning the measurements of the conductivities of gases through which the radiations from radioactive substances are passing, the original investigations, especially of Rutherford, must be consulted.

PROPERTIES OF THE RADIATIONS GIVEN OUT BY RADIOACTIVE SUBSTANCES

We have already become familiar with the fact that radioactive substances give out radiations that have the property of affecting a photographic plate, of rendering certain substances phosphorescent, and of ionizing gases.

The question would naturally be raised, are the radiations given out by all radioactive substances the same in character? Again, are all the radiations given out by any one radioactive substance of the same nature?

These questions are easily asked, but can be answered only by experimental work, and this not always of a very simple kind. It is, however, not a difficult matter to show qualitatively that the radiations given out by a radioactive substance, such as radium, are not homogeneous, but are *complex* in character.

If we charge a gold-leaf electroscope and subject it to the radiation from radium, it will be rapidly discharged, due to the ionization of the air produced by these radiations. If now we interpose between the radium salt and the electroscope a thin sheet of metal, or even a piece of paper, the electroscope will be discharged much more slowly, showing that a portion of the radiation has been cut off. If we then interpose into the path of the rays a thick piece

of metal, the electroscope will be discharged much more slowly than when a piece of metal foil was used, and the difference will not be proportional to the thickness of the piece of metal introduced. The interposition of a second such piece of metal has but little effect.

These qualitative experiments show conclusively that the radiation from radium is heterogeneous, consisting of different kinds of rays. The most natural interpretation of these results would be that the piece of thin sheet metal, or metal foil, cuts off a kind of radiation that has relatively little power to penetrate matter; and that the thick piece of metal cuts out a more penetrating kind of radiation, letting a third, highly penetrating form pass through, which of itself is capable of ionizing the gas to a slight extent and slowly discharging the electroscope.

While this is, perhaps, the most obvious interpretation of the results of the above described experiment, it remains to be seen whether it is the correct one.

Giesel[1] took up the study of the effect of the magnetic field on the radiations from radium in general. Results of the very highest importance were obtained. He found that at least some of the radiations from radium could be deflected by the magnetic field, which accounted for the change in the conductivity produced in the air by the radiations when these were made to pass through a magnetic field.

A little later M. Curie[2] showed that the radiations from radium consisted of two kinds, one that was not deflected or deviated in the magnetic field, and another that was deviated by the field. The kind that was not deviated had very little penetrating power, and was the kind that is so readily stopped even by a thin sheet of metal foil.

[1] Wied. Ann., **68,** 834 (1899).
[2] Compt. rend., **130,** 73 (1900).

The kind that was deviated by the magnetic field had much greater penetrating power, and was capable of passing through thin sheets of metal. It could not, however, pass through sheets of metal of any appreciable thickness.

About the same time it was shown by Villard [1] that the radiations from radium contain a third kind of rays, that have very great penetrating power, and are not deviable by the magnetic field. The radiations from radium contain, then, three kinds of rays, each with its own definite, characteristic properties. These have been named the

Alpha (α) rays.
Beta (β) rays.
Gamma (γ) rays.

We can now understand the qualitative experiment discussed earlier in this chapter.

The thin sheet of metal cut off the α radiations, but allowed most of the β, and practically all of the γ radiations to pass through. When the α rays were cut off the air was ionized much less rapidly, for, as we shall learn, the α rays are the chief ionizing agents in the radium radiations, and the electroscope was discharged much less rapidly than when they were allowed to pass through the air between the leaves of the electroscope.

The thick piece of metal cut off the β radiations and allowed only the γ radiations to pass. The electroscope was now discharged much more slowly, since the γ radiations have less power to ionize a gas than even the β radiations, which in turn have much less ionizing power than the α radiations.

Our original conclusion from the facts of the qualitative

[1] Compt. rend., **130,** 1178 (1900).

experiment is not correct. The radiations from radium possess in some distinct sense of rays.

We shall now proceed to study the properties of these in some detail, taking them up in the order, alpha, beta and gamma, and not in the order of their discovery.

It may be said in advance that all three radioactive substances, uranium, thorium, and radium, give out these three types of radiations. Polonium, as we shall learn, gives out only one type, the α radiations.

CHAPTER VIII

THE ALPHA RAYS

IT has already been mentioned that the α rays are only slightly deviable in a magnetic field, that they have very little power to penetrate matter, and that they produce most of the ionization of the gas through which the radiations from radium pass.

The study of the deviation of the α rays in a magnetic field we owe largely to Rutherford.[1] That they are deviated was shown by the following simple experiment. If some radium salt is placed in the bottom of a narrow tube, which in turn is introduced between the poles of an electro-magnet, radiations from the salt will fall upon an electroscope placed directly in front of the tube. If the current is now turned on the electromagnet, any rays that are appreciably deflected by the magnet would fall upon the side walls of the tube, and would not reach the electroscope.

The number of experimental difficulties that had to be overcome was large. The tube or slit in which the salt was placed must be small, in order that the rays might be bent enough to strike the walls. To augment the effect a number of such slits were used.

After all of the experimental difficulties had been overcome, Rutherford showed that when a powerful magnetic field was used, all of the α rays were deviated. This proved that the α rays are made up of charged particles. It does

[1] Phil. Mag., **5**, 177 (1903).

not, however, show whether the particles are charged positively or negatively. If the particles are charged positively the rays would be deviated in one direction, if negatively in the opposite direction. It was found that the α rays are deviated in a direction which is exactly opposite to that in which another class of rays, known, as we shall see, to consist of negatively charged particles, is deviated. This proves that the α rays, at least from radium, are composed of positively charged particles.

It will be remembered that the α rays are given off from all radioactive substances, and, further, that only α rays are given off from polonium. A question that should be raised and answered is this, are the α rays from polonium the same in character as the α rays from other radioactive substances? This was tested by Becquerel in 1903. He showed that the α rays from polonium are deflected in the magnetic field in the same direction as the α rays from radium. The α rays from polonium, therefore, consist also of positively charged particles.

The conclusion that the α rays consist of electrically charged particles was confirmed by Rutherford in the following manner. The rays were passed through an electric field, and were shown to be deviated by the field. This must be the case if the conclusion that the α particles are charged, is correct.

THE RATIO $\dfrac{e}{m}$ FOR THE ALPHA PARTICLE

The ratio of the charge to the mass of the α particles can be ascertained by the same general method as that which was employed by J. J. Thomson for determining the same ratio for the cathode particle. This has already been discussed at some length in an earlier chapter. By

studying the deviation of the rays in both a magnetic and electrostatic field, as we have seen, it is possible to determine the velocity of the particles and the ratio $\frac{e}{m}$.

Very different results were obtained with the α particles from those reached by Thomson for the cathode particles. The velocity of the α particles is about 2.5×10^9 centimetres per second, which is about one-tenth the velocity of light. The ratio of charge to mass for the α particle is about 6×10^3. While this result must not be regarded as very accurate, on account of the difficulty in obtaining a large deviation in the electrostatic field, it is still of the right order of magnitude.

It is interesting to compare this result with that found for the cathode particle.

The velocity of the cathode particle is about 3×10^9 centimetres per second, and the ratio $\frac{e}{m} = 10^7$.

The cathode particle, therefore, moves faster than the α particle, and has a value of $\frac{e}{m}$ which is about two thousand times as great as that of the α particle.

THE MASS OF THE ALPHA PARTICLE

Knowing the value of $\frac{e}{m}$, we have become familiar with a method worked out by J. J. Thomson for determining the value of e and, therefore, the value of m. While these determinations have not been carried out directly for the α particles as for the cathode particle, still some light has been thrown on the present problem. We have seen that the ratio $\frac{e}{m}$ for the α particle is about 6×10^3.

The ratio of $\frac{e}{m}$ for the hydrogen ion in the solution of acids is, as we have seen, about 10^4.

If the charge carried by the α particle is the same as that carried by the hydrogen ion in solution, as is made highly probable by our general knowledge of these bodies, then we can compare the masses of the hydrogen ion and of the α particle. Since $\frac{e}{m}$ for the former is 10^4, and $\frac{e}{m}$ for the latter 6×10^3, and since e in the two cases is the same, it follows that the mass of the α particle is about *twice the mass of the hydrogen ion*. It will be recalled that the determination of $\frac{e}{m}$ for the α particle is only approximate. It is therefore possible that the mass of the α particle is even four times as great as that of the hydrogen ion, in which case it would be equal to the mass of the helium atom. We shall see that there is some evidence in favor of the view that the α particles are charged helium atoms, and some very recent evidence against this conclusion.

We have seen that the α particles are projected with enormous velocities, 2.5×10^9 centimetres per second. If they have masses even as great as the hydrogen atoms or ions, with such velocities they would have a large amount of energy. This is the probable explanation of their great power to ionize a gas through which they pass, and to produce other effects with which we shall become familiar somewhat later.

THE SPINTHARISCOPE

One other matter must be discussed before leaving the α rays. It has already been stated that strongly radioactive substances like radium can produce phosphorescence in certain substances exposed to their radiations. Thus,

screens covered with barium platinocyanide or zinc sulphide become phosphorescent when exposed to the action of radium radiations.

This power of the radiations from radium to produce phosphorescence can readily be shown to be due mainly to the α rays. If the α rays are cut off by a thin screen of metal, most of the power of the radiations to produce phosphorescence is lost.

The power of the α particles to produce phosphorescence has been utilized by Sir William Crookes[1] in the following manner. If a plate covered with phosphorescent zinc sulphide is exposed to the radiations from radium or polonium, at a short distance from the substance, it presents a remarkable appearance. The screen does not become homogeneously phosphorescent throughout, but bright points of light make their appearance, and rapidly disappear. The best result is obtained by examining the screen through a small lens. Based upon these facts is Crookes' *spinthariscope*. At one end of a tube is placed a piece of metal which contains some radium chloride or bromide on its surface. This is suspended at a distance of a few millimetres from a screen covered with phosphorescent zinc sulphide. The other end of the tube contains a magnifying lens. This instrument has been termed a spinthariscope, from "*spintharis*," a spark.

The appearance of the screen has been described as analogous to that of the milky way as seen with the naked eye on a dark night. Bright points of light appear and quickly disappear all over the screen. These come and go in rapid succession. The effect has also been described as analogous to the splashing of drops of rain in a pool.

The cause of this remarkable phenomenon is probably

[1] Roy. Soc. Proceed., **71,** 405 (1903). Chem. News, **87,** 157 (1903).

the impact of the α particles upon the screen covered with the substance in which phosphorescence can be set up. The α particles, on account of their high velocity and appreciable mass, have, as we have seen, a considerable amount of kinetic energy. When they fall upon the screen covered with zinc sulphide, they are stopped, and produce a mechanical disturbance. Zinc sulphide becomes luminous when subjected to almost any mechanical disturbance. Merely rubbing it with a hard surface will render it phosphorescent. Wherever an α particle falls upon the screen, that portion of the screen becomes luminous for some distance around the point of collision. Every spark or centre of luminous disturbance on the screen is the result of the impact of an α particle upon the screen. We thus see, as it were, the points at which the separate α particles strike the phosphorescent screen, and this is, perhaps, one of the best examples of the *action of individual atoms or molecules made directly perceptible to any of our senses.*

Another theory of the action of the spinthariscope has been proposed by Becquerel.[1] He thinks the scintillation is due to a fracture of the crystal of the phosphorescent zinc sulphide by the α particles. He does not think that such a fracture could be produced by one α particle, but only when a number of such particles strike simultaneously a weak point in the crystal. That light is frequently emitted when crystals are crushed, is well known. Indeed, crystals of zinc sulphide give out light when mechanically crushed, and according to Becquerel such light has the characteristics of that in the spinthariscope. It shows the same general kind of scintillations, and the number of scintillations is dependent somewhat upon the size of the crystals of zinc sulphide with which the screen is covered. The

[1] Compt. rend., **137, 629** (1903).

smaller the crystals of the sulphide the larger the number of scintillations, which accords with Becquerel's view as to the action in the spinthariscope. The smaller the crystals the more easily they would be broken, and, consequently, the larger the number of scintillations. It is difficult at present to decide between these two views. The theory first advanced is the simpler and more fascinating, but it may not be true. More experimental evidence must be obtained before a final decision can be reached.

CHAPTER IX

THE BETA AND GAMMA RAYS

THE BETA RAYS

IT was pointed out in connection with the study of the α rays, which are only slightly deviable, that the radium radiations contain rays which are readily deviated by the magnetic field. This was shown by means of an experiment already referred to in connection with the study of α rays.

Some radium bromide was placed on the bottom of a tube of lead, which in turn was introduced between the poles of an electromagnet. In front of the tube, and at a distance of several centimetres from it, was an electroscope. It is necessary that an air space should intervene between the tube and the electroscope, in order that the α radiations from the radium should be cut off and not allowed to fall upon the instrument. A few centimetres of air are quite sufficient to cut off the easily absorbed, non-penetrable α rays, as we have seen. The β radiations from the radium now fall upon the electroscope, together with the γ radiations; but since the latter have only very small power to ionize a gas through which they pass, they have but little power to discharge the electroscope. Further, they are not deflected by a magnetic field, and, therefore, their action on the electroscope is constant before and after the current is turned on the electromagnet.

When the electromagnet is turned on and a magnetic

field established, the β rays are readily deflected against the walls of the tube, and no longer fall on the electroscope, or ionize the air between the leaves. The electroscope is now discharged much more slowly than before the magnetic field was produced. This experiment illustrates qualitatively the deviable nature of the β rays.

A question in this connection which is of importance is this: Are all the β rays equally deviable? Are the β radiations homogeneous? This is answered by the following experiments.

If in the preceding experiment the metal tube was covered with a metal plate having a narrow slit cut in it, only a narrow beam of rays could escape from the tube. This would produce only a narrow line on a photographic plate. If the magnetic field is now established, the β rays will be deflected to one side. The impression upon the plate, however, is *not* that of a displaced narrow line, but is a broadened band. This shows that the deviable β rays are not homogeneous, but that some are more deflected by the magnetic field than others. They are spread out by the magnetic field into a kind of spectrum, showing that some of the β particles have very different velocities from the others.

NATURE OF THE CHARGE CARRIED BY THE BETA PARTICLES

The β rays, as we have seen, are deflected in the magnetic field. The next question is, are they charged, and if so, positively or negatively? This is answered by the following experiment carried out by M. and Mme. Curie.[1]

If the β rays are absorbed by any substance they would necessarily give up their charge to the absorbing medium. It would, apparently, be only necessary to detect the *nature*

[1] Ann. Chim. Phys. [7], **30**, 155 (1903).

oj the charge on the object by which the β rays are absorbed, in order to determine the *nature* of the charge carried by the β rays themselves.

While this at first sight is a very simple matter, a difficulty is encountered. The β rays produce ions in a gas through which they pass. These would conduct the charge away from the object upon which the β rays impinge, and not enough charge would collect to be detected. In carrying out such an experiment it would obviously be necessary to cut off the α rays by means of a thin sheet of metal, through which the β rays would pass, since the α rays have much greater ionizing power than the β rays. Even when this is done the β rays render the air a sufficiently good conductor to remove the electricity too rapidly from the object which absorbs the β rays, in order that a sufficient charge should accumulate to be detected.

This difficulty was overcome by the Curies by imbedding the plate upon which the β rays were to fall, in an insulator through which the β rays could pass. They used thin ebonite, and also a thin layer of paraffine. The result was, that the Curies were able to demonstrate that the metal upon which the β rays fell, *became charged negatively*. This proved that the β *particles carried a negative charge*. The same result was obtained by Wien, who surrounded the plate upon which the β rays were to fall, not with an insulator, but with an evacuated vessel.

The Curies proved that the plate *continually received negative electricity*, as would be expected by the constant raining of the negatively charged β particles upon it. Mme. Curie states that only a very weak current was obtained under the above conditions, as would be expected.

The Curies then undertook the sequel to the above experiment. If the β rays are charged negatively, they must

leave the radium from which they are shot off positively charged. To test this conclusion the Curies placed the radium salt in a lead box, and surrounded the whole with the insulating medium. The insulating material was then surrounded by metal connected to earth.

Under these conditions the *radium became positively charged*, due to negative charges being carried off by the β particles, which, in this case, were communicated to the outside metal box and then to earth.

In the above experiment the α particles are completely absorbed by the insulated box, and their effect thus reduced to zero.

An interesting observation in this same connection has been described by the Curies. Radium would continue to throw off negative charges until it itself would become so highly charged positively that this would prevent the further sending off of negative charges. An active preparation of radium was sealed up for some time in a glass tube. When the tube was scratched with a file, the weakened portion was at once perforated by a spark, and M. Curie at the same moment received an electric shock. The potential of the tube had thus been raised well above the potential of the earth, due to the absorption of the positively charged α particles, which gave up their charge to the inside of the tube.

THE DETERMINATION OF $\dfrac{e}{m}$ FOR THE BETA PARTICLE

We have already studied the method worked out by J. J. Thomson for determining the ratio of $\dfrac{e}{m}$ for the cathode particle. This method, it will be remembered, is based upon subjecting the cathode rays to both electrostatic and

magnetic deflection. Exactly the same method was used with the β particles from radium. It is not necessary to repeat the discussion of this method. If necessary, the account of the method given in an earlier chapter should be reread. The velocity of the β particles, as thus determined by Becquerel, was about 1.5×10^{10} centimetres per second, and the value of $\frac{e}{m} = 10^7$. This velocity is of the same order as that of light, 3×10^{10} centimetres per second, and is considerably greater than that found for the cathode particle in the low-pressure tube.

One matter of very great importance in this connection must be mentioned again. It will be remembered that all of the β particles are not deflected equally by a magnetic field. This was shown by a broadening of the line on the photographic plate, when the magnetic field was produced. It was pointed out that this was due to the fact that the β *particles did not all move with the same velocity.*

This is made the basis of the important experiment of Kaufmann, to which reference has already been made. He studied the electrostatic and magnetic deflections of the β rays having different velocities, and determined the value of $\frac{e}{m}$ for the different rays.

He found that *this value was not constant, but varied with the velocity of the particle.* The value of $\frac{e}{m}$ increased as the velocity of the particle diminished. This is seen from the results, already discussed in an earlier chapter, see page 20.

The importance of this observation has already been pointed out. The charge e carried by the particle is constant, independent of the velocity. Since $\frac{e}{m}$ changes with

the velocity, we must conclude that m, or the *mass of the particle, changes with the velocity.*

The significance of this has already been referred to in an earlier chapter. It will be remembered that the conclusion to which we were led, especially after comparing the values calculated by Thomson with those found experimentally by Kaufmann, is that *all mass is of electrical origin,* and that matter is made up of electrons or disembodied electrical charges, moving with high velocities.

THE MASS OF THE BETA PARTICLE — RELATION TO THE CATHODE PARTICLE

The method for determining the mass of a particle, knowing the value of the ratio $\frac{e}{m}$ for it, has already been discussed at length. The mass of the β particles is about $\frac{1}{770}$ the mass of the hydrogen ion in solutions of acids. *It is, therefore, the same as the mass of the cathode particle.*

We have now studied a sufficient number of properties of the β rays to enable us to make a comparison with the corresponding properties of the cathode rays.

CATHODE RAYS

Affect the photographic plate.
Excite phosphorescence.
Ionize a gas.
Are negatively charged particles.
Have moderate power to penetrate matter.
Have a mass about $\frac{1}{770}$ of the mass of the hydrogen ion.
Have a velocity about one-tenth that of light.

BETA RAYS FROM RADIUM

Affect the photographic plate.

Excite phosphorescence.

Ionize a gas.

Are negatively charged particles.

Have moderate power to penetrate matter.

Have a mass about $\frac{1}{770}$ of the mass of the hydrogen ion.

Have a velocity that varies for the different β particles, but the mean velocity is about half that of light.

We see from the above that the β particles resemble the cathode particles very closely in all of their properties, except the velocity with which they travel. That the two sets of particles should *not have the same velocities*, is not at all surprising, when we consider the different conditions under which they are produced.

The β particles are shot off from radium with velocities that are *definite*, and which are conditioned by the *nature of the substance*. The cathode particles are shot off from the cathode under a high electrical stress, conditioned in part by the difference between the potential of the anode and the cathode. Indeed, we should expect that the velocity of the cathode particle would vary with the field that was employed, and such is the fact. With a strong field the velocity of the cathode particle is greater than with weak fields, and with very strong fields the velocity of the cathode particle approaches much more nearly to the velocity of the β particle.

We can, then, *regard the β particles as essentially identical with cathode particles, differing from them only in the velocities with which they move.* This would produce, as we have seen, a slight difference in the mass, but it is not necessary to go further into this matter in the present connection.

We have learned that the cathode particles are nothing but electrons, or disembodied, negative electrical charges.

Therefore, the β rays are made up of nothing but negative electrical charges, shot off from the radium with enormous velocities — the velocities being comparable with that of light.

We have learned that all the radioactive substances known give off α particles. The three radioactive substances, uranium, thorium, and radium, give off β particles. Polonium, as we have seen, gives out only α particles.

THE GAMMA RAYS

A third kind of rays is given out by all radioactive substances, with the exception of polonium. It was shown by Villard, as we have seen, that these rays are *not deviated* by a magnetic field, and have much greater power to *penetrate matter* than either the α or the β rays. A thin film of metal is sufficient to stop the α rays. The β rays are all cut off by a piece of some heavy metal like lead that is a centimetre thick, while the kind of rays with which we are now more especially dealing can, according to Rutherford, be detected by a sensitive electroscope after they have passed through a piece of iron that is a foot thick.

These rays have not as yet been deflected to a detectable amount in the magnetic field.

While all the radioactive elements, with the exception of polonium, give off β rays, they give them out with very different intensities. It would be expected that the weakly radioactive elements, uranium and thorium, would give out γ rays to a less extent than the highly radioactive radium, and such is the fact. The γ rays given out by the weakly radioactive elements have, however, been detected by using fairly large quantities of these substances.

The γ rays, therefore, always accompany the β rays, and this is a matter of importance in connection with the theories

that have been advanced to account for the nature of the γ rays.

Two hypotheses as to the nature of the γ rays have been proposed.

We have seen that the β rays are made up of electrons, or negative electrical charges, moving with different velocities, but all having very high velocities; the swiftest of these travelling with a velocity which is nearly that of light. It is possible that electrons are shot off from radium with even a higher velocity than that of the swiftest β rays. Such rays could have at least some of the properties of the γ rays. Their great penetrating power might be due to their large kinetic energy resulting from their great velocity. The fact that they are not deflected in the magnetic field has been accounted for by the advocates of this theory, on the ground that the amount of the deviation being an inverse function of the velocity, the more rapidly moving particles might be deflected to such a small extent that it would not be observed. This theory contains a number of weak points. In the first place, the penetrating power of the γ rays is so many times that of the β rays that it seems difficult to account for this on the basis of the slightly increased velocity, even if the velocity of light is being closely approached. Further, if this theory as to the nature of the γ ray is correct, we might reasonably expect to find rays with penetrating power intermediate between that of the β ray and the incomparably greater power of the γ ray. Indeed, all the intermediate stages could easily be represented. Such, however, is not the fact. The same criticism holds with respect to the deviation in the magnetic field. If γ particles are nothing but more rapidly moving β particles, and if the fact that the β particles are so readily deflected the magnetic field, while the γ particles are not deflected

at all, are to be accounted for solely on the ground of the difference in velocities, then why do we not find the intermediate stages represented? This question is especially pertinent in consideration of the fact that we do know β particles with quite different velocities. The magnetic deflection of even the swiftest of these is *easily* detected. If β particles with intermediate velocities existed, it seems reasonable to think that there would be no serious difficulty in detecting their deflection in a magnetic field.

A theory as to the nature of the γ rays, which accounts much better for many of the facts, is the following. We have seen in a much earlier chapter, that whenever cathode rays strike a solid object X-rays are produced. We have recently seen that the β rays are essentially identical with the cathode rays. We would naturally expect that X-rays would be set up where the β rays strike a solid object. The β rays from radium strike some of the solid radium salt, or some other solid, and the γ or X-ray is accordingly produced. The γ *ray, in terms of this theory, is nothing but an X-ray.* We have seen, however, that it has much greater penetrating power than the X-ray, and it must therefore be regarded as a *very penetrating kind of X-ray.*

This theory accounts satisfactorily for the entire absence of deflection of the γ rays in a magnetic field, since ordinary X-rays are themselves entirely undeflected by such a field.

This theory as to the nature of the γ rays also accounts for the fact that γ rays are always absent unless β rays are present.

Some objections have, however, been offered to this theory as to the nature of the γ rays, so that it must not be regarded as final.

SUMMARY OF THE PROPERTIES OF THE ALPHA, BETA, AND GAMMA RAYS

The a rays are given off by all radioactive substances. They are somewhat deflected in a magnetic field. They have very small penetrating power, being easily absorbed even by very thin layers of matter. They have great power to ionize a gas, rendering it a conductor. The *a* rays ionize to about one hundred times the extent of the β and γ rays together. They have but little effect on a photographic plate, but produce phosphorescence in certain substances, especially zinc sulphide. The existence of phenomena such as those manifested in the spinthariscope are due almost entirely to the *a* particles. The *a* particle has a mass of the order of magnitude about twice that of the hydrogen ion. This, however, is only an approximation. The *a* particle carries a positive charge of electricity, and moves with a velocity about one-tenth that of light.

The β rays are given off from all radioactive substances, with the exception of polonium. They are very easily deflected in a magnetic field. They are absorbed by matter, but not near so easily as the *a* rays. They have comparatively small power to ionize a gas. They do not have great power to affect a photographic plate, and while they can produce phosphorescence are less active in this respect than the *a* particles.

The β particle has a mass about $\frac{1}{1710}$ of the mass of the hydrogen ion in solution, which is the mass of the electron. The β particle carries a unit charge of negative electricity, or, more accurately expressed, is a unit negative charge of electricity, shot off with an average velocity which is of the same order as that of light.

The β ray is practically identical with the cathode ray in

a vacuum tube, differing from it chiefly in the velocity with which the particles move.

The γ rays exist where the β rays exist. They are not deflected at all in a magnetic field. They have very great penetrating power, enough passing through a foot of iron to be detectable by the electroscope. They have much smaller power than the α particles to ionize a gas. They have considerable power to affect a photographic plate, much greater than the α or even the β particles. They excite phosphorescence. The most probable theory as to the nature of the γ rays is that they are a very penetrating form of X-ray, produced by the β rays. They are, therefore, pulses in the ether, set up by the impact of the β rays on solid matter.

CHAPTER X

OTHER PROPERTIES OF THE RADIATIONS

WE have already studied a number of the properties of the several kinds of radiations, and have compared the one with the other. We shall now take up certain special properties of the several kinds of radiations sent out by radium, as pointed out by Mme. Curie.[1]

THE SELF-LUMINOSITY OF RADIUM COMPOUNDS

While the comparatively pure radium salts give out only a little light, radium salts which contain a large amount of barium are strongly self-luminous. This fact was observed by the Curies. The dehydrated, dry, halogen compounds of radium are especially self-luminous. While the self-luminosity cannot be perceived in ordinary daylight, it can be seen by gaslight. The self-luminosity comes from the entire mass of the radium salt, and not simply from the surface. In the presence of moist air the salt loses a large amount of its self-luminosity, but this is again regained on drying the preparation. The self-luminosity persists for a long time. Specimens preserved for years in the dark still continue to be self-luminous. Mme. Curie points out that the color of the light emitted from strongly radioactive preparations changes with time, becoming more violet and decreasing in intensity. The original intensity and color are regained by recrystallizing the salt from water. The

[1] Ann. Chim. Phys. [7], **30,** 145 (1903).

luminosity of the radium salt is apparently independent of temperature. Solutions of radium salts are slightly self-luminous. The crystals in such a solution are more strongly self-luminous than the solution, and can be seen by the light which they emit.

Mme. Curie also points out that *radium is the only substance known that is self-luminous*. It will be remembered that radium is the only substance known that has the power to *charge itself electrically*.

PHOSPHORESCENCE PRODUCED BY RADIUM SALTS

That salts of radium are capable of exciting phosphorescence in certain substances has already been mentioned. This was first discovered by the Curies. It was subsequently studied by others, and especially by Becquerel. Thus, the diamond, ruby, the sulphide of calcium, zinc sulphide, barium platinocyanide, paper, glass, etc., have been tested.

The action of the radium is, however, not the same as that of the X-ray in producing phosphorescence. Certain substances phosphoresce when exposed to the X-ray, that do not in the presence of radium, and *vice versa*. In this respect the action of radium resembles more closely that of ultra-violet light.

Paper, cotton, as well as certain varieties of glass phosphoresce in the presence of radium. This is especially true of Thuringian glass. Under the action of radium the glass that phosphoresces becomes colored violet to brown. When the glass has become colored its power to phosphoresce is diminished. If the glass which has become colored and has lost its power to phosphoresce is heated, the color is lost and the power is again regained. Barium platinocyanide is the best substance with which to study this action of

radium salts. It shows phosphorescence when placed two metres from active radium.

Zinc sulphide, as we have seen, is also rendered phosphorescent by the radium rays. It is especially sensitive to the action of the α rays, where it shows the characteristic scintillations in the spinthariscope. It has already been mentioned that the diamond becomes phosphorescent in the presence of radium, and can thus be distinguished from the imitation.

While all three kinds of rays produce phosphorescence, the α rays, on the whole, are the most active. This can be seen by interposing between the radium and the screen a thin piece of metal foil or of paper which will cut off the α particles. The β and γ rays can also produce phosphorescence, especially in screens of barium platinocyanide. Their power is, however, much feebler than that possessed by the α particles.

RADIUM INCREASES THE CONDUCTIVITY OF DIELECTRICS

The property of radium to ionize a gas and render it a conductor has already been repeatedly mentioned. A good qualitative method of demonstrating this power is the following: Take an induction coil and place the discharging points just so far apart that a spark will cease to pass. Then place a glass tube containing a few milligrams of an active radium salt between the two points. The discharge will take place at once. This is due to the ionization of the air between the terminals by the radiation from the radium. In the above case most of the ionization is produced by the γ rays, since most of the α and β rays are cut off by the glass. If the radium salt were placed in an open vessel so as to secure the ionizing effect of the strongly ionizing α rays, the conductivity of the gas would be still more increased.

The *conductivity* of a number of *liquid non-conductors* is very considerably increased by exposing them to the radium radiations. Thus, a number of our best liquid insulators acquire a measurable conductivity under the influence of the radiations from radium. This applies to carbon disulphide, petroleum ether, liquid air, vaseline oil, etc.

It would seem that this ionization in liquids was produced mainly by the γ radiations, since similar results were obtained by M. Curie when the liquids were exposed to X-rays, with which, it will be remembered, the γ rays are closely allied. Similar results have been obtained with certain solid dielectrics. Thus, paraffine exposed to the radiations from radium acquires some conductivity. The ionization produced in the paraffine, as well as in the liquid non-conductors, is probably due mainly to the more penetrating rays from radium.

CHEMICAL EFFECTS PRODUCED BY RADIOACTIVE SUBSTANCES

The crystalline halogen salts of the alkalies — the chlorides, bromides, etc., are colored by radium radiations as by cathode rays. The Curies observed that glass and porcelain became colored when exposed to radium. A violet or brown color appears in the glass, which persists after the removal of the radium. Glass which has been exposed for a considerable time to the action of radium becomes darkened. This is apparently true of all glasses.

Mme. Curie subjected a number of glasses of known, but widely different composition, to the action of the radium radiations, and concluded that the coloration was due to the presence of the alkali metal in the glass. Salts of the alkali metals themselves showed more vivid coloration, and a greater variety of colors than the different glasses that were studied by Mme. Curie.

The most probable theory as to the cause of the coloration in glass is that the radiations from radium liberate the alkali metals, which then form a solid solution in the glass.

Radium transforms oxygen into ozone, which can be detected by its odor. This is due to the α and β rays, since, when these are cut off, no ozone is produced. To understand what this transformation really means, we must ask the question, what is the real difference between oxygen and ozone? The older text-books on chemistry state that the difference in the properties of oxygen and ozone is to be referred to the fact that oxygen contains two atoms in the molecule, and ozone three. It is obvious that this explains nothing, except the difference between the mass of the atom of oxygen and the mass of the atom of ozone. The chemical and physical properties, in general, of substances cannot be explained on any material bases. To gain any rational conception of them we must take into account the *energy relations and conditions* that exist in the substance in question.

It is a simple matter to prove that the real difference between the properties of oxygen and ozone is due to the *different amounts of intrinsic energy* possessed by their molecules. If we burn carbon in oxygen or in ozone, the same end product, carbon dioxide, is obtained. If oxygen and ozone contain different amounts of intrinsic energy, there will be different amounts of heat liberated when the same amounts of carbon are burned in the two gases; since the amount of heat liberated in any case is the thermal expression of the difference between the intrinsic energy of the system before a reaction has taken place, and after the reaction is completed.

If we burn a given weight of carbon in ozone, *more heat is liberated* than when we burn the same weight of carbon

in oxygen. Since the same amounts of carbon dioxide are formed in the two cases, we must conclude that *ozone contains more intrinsic energy than oxygen*, and any differences in the properties of these two allotropic modifications of the same element are to be referred to the different amounts of intrinsic energy possessed by their molecules. Radium, then, adds energy to oxygen, transforming it into ozone, and this is accomplished mainly by the α and β rays. This is in keeping with our knowledge of the radiations given off from radium, since most of the energy is contained in the α particles. According to Becquerel, radium radiations can also transform white phosphorus into red.

Radium compounds undergo changes themselves under their own radiations. When the method of separating radium from pitchblende was under discussion, it was pointed out that crystals of radium chloride with which barium chloride was mixed, while colorless when first formed, became quickly colored. The color is lost by recrystallizing the salt. The coloration produced by the radium salts extends more deeply into the substance than that caused by the cathode rays.

It has already been mentioned that the radiations from radium affect a photographic plate. This is, of course, due to a chemical action on the silver salt of the photographic plate. Polonium acts on a photographic plate only when the plate is brought very near to the substance. This is due to the fact that polonium gives out only α rays, which have weak photographic action; and further, are largely absorbed by a layer of air, even a few centimetres in thickness.

Radium, however, acts at much greater distance on a photographic plate. It produces a marked impression at a distance of several feet, even when the radium is inclosed

in a glass tube, which cuts off all of the α rays, and some of the β. We have seen that it is the γ rays that are especially active photographically. It has been found that the best *radiographs* are produced by the γ rays alone.

PHYSIOLOGICAL ACTION OF THE RADIATIONS FROM RADIUM

Fairly active radium is capable of producing burns or wounds when brought near the skin, that are both painful and slow to heal. The skin is first inflamed and reddened, and may actually become blistered if exposed for a sufficient length of time close to an active preparation of radium.

The action of the radiations from radium upon certain diseases of the skin, such as lupus, has been tested, and apparently has yielded good results in the hands of the dermatologist. It has also been claimed to have produced wholesome effects upon cancerous tissue, especially in the early stages. Whether it is really capable of curing this disease remains to be seen. It is certainly true that the radiations from radium are more penetrating than ultra-violet light or X-rays, which have been shown to have certain curative properties. They can, therefore, penetrate more deeply into the tissue, and might give better results.

An interesting physiological experiment has been studied by Himstedt and Nagel.[1] If a preparation of radium is brought near the closed eye in a dark room, a sensation of light is produced. This is due to the phosphorescence produced within the eye itself by the radium, the lens and retina being strongly phosphorescent under the action of the β and γ rays. This sensation is experienced even by the blind, if the retina has not been destroyed.

Aschkinass and Caspari have shown that the radiations from radium also diminish the activity of certain bacteria.

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[1] Ann. d. Phys., **4,** 537 (1901).

A large number of facts in connection with the action of radium upon living matter have been brought to light. It would obviously lead too far to discuss these at length in the present connection.

The physiological action of radium is due mainly to the α and β rays. These are cut off by placing the radium salt in a metal box — especially in one of lead. This precaution should always be taken when active preparations of radium are being used.[1]

[1] For further details in reference to the matters discussed in this chapter, see the article by Mme. Curie in Ann. Chim. Phys. [7], **30,** 186–203 (1903).

CHAPTER XI

Production of Heat by Radium Salts

An observation of the greatest importance was made in 1903 by M. Curie and Laborde.[1] *Salts of radium have a temperature that is continually above that of the surrounding medium.* This means that heat is being produced in the radium compound. That the radium salt is warmer than the surrounding air can be shown qualitatively by means of fairly sensitive mercury thermometers. It can be readily demonstrated in the following manner, according to Mme. Curie. A double-walled glass bulb was made, and the space between the two walls exhausted. The object of removing the air was to render the space between the walls a very poor conductor of heat. Into such a vacuum-jacketed vessel the bromide of radium, placed in a glass tube, was introduced, together with a relatively sensitive thermometer. Into a second such vessel a similar thermometer was introduced. The thermometer placed near 0.7 of a gram of the radium salt registered two or three degrees higher than the thermometer in the vessel that contained no radium. Thus, quite appreciable differences in temperature were produced with a few decigrams of the radium compound. With larger quantities of the salt still greater differences in temperature would result.

MEASUREMENT OF THE HEAT LIBERATED BY SALTS OF RADIUM

Several methods have been employed to measure the *quantity of heat* liberated in a given time, by a given quantity

[1] Compt. rend., **136**, 673 (1903).

of radium. A rough method carried out by M. Curie and Dewar is more novel and interesting than important. It is well known that Dewar, provided with the splendid low-temperature plant of the Royal Institution, has been able to obtain in large quantities all of the lowest condensing gases, with the exception of helium, in the liquid form.

He has obtained liquid hydrogen in considerable quantity, and worked out a number of its interesting properties. He has determined its boiling-point, and found this to be only about twenty on the absolute scale, which is -253 degrees centigrade. If heat is added to liquid hydrogen it will boil. On account of the very low temperature at which liquid hydrogen boils, it will take up heat from any surrounding liquid except more of the liquid hydrogen itself, and would thus continue to boil without cessation, or at least to give off appreciable quantities of hydrogen gas.

A test-tube, whose lower half was surrounded by a double-walled, vacuum jacket, was filled about one-third full with liquid hydrogen. This was then immersed in a larger vessel, also surrounded by a double-walled vacuum jacket, and the space between the two filled with liquid hydrogen. The hydrogen in the inner tube soon ceased to give off any appreciable amount of gas, since it could not obtain the heat necessary to convert itself into vapor — the conduction of heat being prevented by the hydrogen in the outer vessel, which always continued to give off gas. If any heat was supplied to the liquid hydrogen in the inner vessel, a part of the liquid would be converted into vapor which would escape.

The experiment consisted in arranging the system as above described, and waiting until the gas ceased to escape from the inner vessel. A weighed quantity of the radium salt, sealed up in a glass tube, was then introduced into the

liquid hydrogen in the inner tube. The tube and salt being at ordinary temperatures when introduced into the liquid hydrogen, would give up heat to the liquid until they were cooled down to the temperature of the liquid hydrogen itself. This would, of course, volatilize a part of the liquid, and gaseous hydrogen would escape. After the small glass tube containing the radium salt and its contents had been cooled to the temperature of the liquid hydrogen, gas would cease to escape from this tube, unless the radium gave off heat. In fact, gas continued to escape from the tube, as long as any liquid hydrogen remained in the vessel. This was due to the heat being given off continuously by the radium.

It is obvious that the amount of hydrogen gas set free in a given time can be used to measure the rate at which heat is being liberated by the radium. It is only necessary to collect the hydrogen and measure it by any of the methods for measuring a gas, and to determine the heat of vaporization of hydrogen, *i.e.*, the amount of heat required to produce, say, 100 cubic centimetres of hydrogen gas, from the liquid. Weighing the amount of pure radium salt that was introduced into the liquid hydrogen, we have all the data necessary for calculating the rate at which radium liberates heat, or the amount of heat produced by a given quantity of radium in a given time. While this method is far less accurate than the one to be described subsequently, it is useful as a confirmatory check; and interesting when we think that the liquid which is vaporized by the heat spontaneously produced by radium is one that was unknown until the last few years, and one which defied the skill of so many able experimenters to produce, including the immortal Faraday.

This method of measuring the amount of heat liberated

by radium has one feature which is of special importance. The radium is giving off heat, under these conditions, at the temperature of liquid hydrogen, which is only about twenty degrees centigrade above the absolute zero. By comparing the results of this method with those of methods that can be employed at ordinary temperatures, we can see what effect temperature has on the rate of heat production by radium.

If the production of heat in salts of radium is due to any chemical action, we should expect that the rate at which heat is evolved by radium would be greatly lessened at the very low temperature, since nearly all chemical reactions take place more slowly the lower the temperature. Indeed, most chemical reactions fail to take place at all at the temperature of liquid hydrogen.

It has been found that *radium liberates just as much heat at the temperature of liquid hydrogen, as at ordinary temperatures.* This alone makes it highly improbable that the heat liberated by radium in its salts is due to any chemical action taking place within the compound. We shall see later that the *amount of heat* liberated by salts of radium is of an order of magnitude so much greater than that known in the case of any chemical reaction, that this source of the heat energy is almost certainly excluded. Further, the fact that salts of radium continue to produce heat for apparently an almost indefinite time, excludes the possibility that it is produced as the result of chemical action.

METHOD OF THE BUNSEN ICE CALORIMETER

The amount of heat liberated by salts of radium is measured most accurately by means of the *Bunsen ice calorimeter*. The principle of this instrument is so well known that only a few words of explanation are necessary. The

essential feature of this method is the use of a block of ice, which is melted by the heat that it is desired to measure. Knowing the amount of ice converted into water and the heat of fusion of ice, we have all the data necessary for determining the amount of heat set free in the ice calorimeter.

In some of the earlier work with the Bunsen ice calorimeter, the amount of water produced was obtained by collecting it and then weighing it. A more accurate method of determining the amount of ice that has been melted is based upon the fact that the ice and the resulting water occupy different volumes. When water freezes the volume increases, and, conversely, when ice melts the volume occupied by the resulting water is less than that occupied by the ice. This principle is utilized to determine the amount of the ice melted.

RESULTS OF HEAT MEASUREMENTS

The results are certainly surprising on account of their enormous magnitude. *A gram of radium gives out every hour about eighty calories of heat.* Since the heat of fusion of ice is eighty calories, or eighty calories of heat are required to melt one gram of ice, it follows that *radium gives out enough heat to melt its own weight of ice every hour.*

The most remarkable feature of all, is the fact that radium continues to give out heat at this rate for apparently an indefinite time. We shall see later that this would go on as long as the radium itself continues to exist.

This is a most surprising result. Indeed, it is one of the most startling facts that has ever been discovered in any branch of physical science. Think of the enormous amount of energy that this substance is capable of liberating!

SOURCE OF THE HEAT

The question naturally arose whence came this energy? Some rushed to the conclusion that it must be created by the radium, and that the law of the conservation of energy was overthrown. Those who were less radical concluded that radium must have the power to transform some unknown kind of energy into heat, which was essentially the same as to admit that they did not know, and had no tangible conception of the origin of this energy.

The more conservative began to look around for a rational explanation of this astonishing and most important fact, in the light of what was known, or what could be discovered.

We shall see a little later that their efforts were rewarded, and that we have a rational explanation as to the origin of the enormous amount of energy given out by radium.

We have seen, then, that very large quantities of energy are liberated by the element radium, and that this continues unabated for practically an unlimited time.

The heat is given off slowly, compared with the heat that is given out in certain combustions. This is the reason that the radium salt does not heat itself to a higher temperature above the surrounding medium. Another explanation of why larger differences in temperature do not exist, is that such small quantities of radium salts have thus far been obtained, that the heat is lost by conduction through the relatively large surface exposed to surrounding objects. If large amounts of radium could be obtained, it is quite certain from the rate at which heat would be produced, that the interior of a pile of radium chloride or bromide would become quite hot; and by suitably surrounding the salt with a medium that was a poor conductor of heat, it is quite possible that the interior of a pile of radium salt

might become red-hot and actually give off light, due to the heat spontaneously produced by itself.

EFFECT ON SOLAR HEAT

The fact that radium gives out heat energy has been utilized to explain certain natural phenomena, for which a satisfactory explanation has long been wanting. Take the heat of the sun, how is it produced? A number of theories have been advanced. The possibility of the heat of the sun being the result of combustion or any chemical action has long since been abandoned. A similar fate has befallen the theory that solar heat is produced by meteoric bodies raining down from space on to the sun. Both of these views have been found to be insufficient in the light of well-known facts.

The theory that is held to-day is that the origin of solar heat is to be found in the *contraction* that is going on in the sun itself. This contraction would, of course, produce a constant shrinking, and a dropping in of the exterior, which would give rise to heat; and in the case of a body of the dimensions of the sun, would give rise to enormous amounts of heat.

This theory is to be sharply distinguished from the older one, that the sun is simply a cooling body, giving out solar heat as it cools. According to the present theory enormous amounts of heat are being *continually produced* in the sun, while according to the cooling theory the sun is simply giving out heat like any other hot body.

This theory of the origin of solar heat has been found to account for the facts. A contraction which would be too small to be observed during the time that careful solar measurements have been made, would account for all the heat given out by the sun during this period.

While this theory is capable of accounting for solar heat, there has, however, been a reservation in the minds of men of science, which has made them hesitate to accept the theory as the final explanation of the origin of all solar heat.

The discovery of the large amount of heat liberated by radium has been utilized by Rutherford[1] to account for at least a part of the solar heat. If the sun consists of a very small fraction of one per cent. of radium, this would account for the heat that is given out by it.

The fundamental question in connection with this theory as to the origin of all or part of the solar heat is this: Does the sun contain radium? Is there any evidence, direct or indirect, that radium exists in the sun?

It must be said that no direct evidence has as yet been produced to show the presence of radium in the sun. The supposed discovery of the spectrum lines of radium in the sun leaves much to be desired. The supposed coincidences of the solar lines with the known lines of radium are only rough approximations. Indeed, so rough that they are far from being convincing.

DOES RADIUM EXIST IN THE SUN?

Indirect evidence of the presence of radium in the sun, however, exists. It has been shown by spectrum analysis that helium exists in the sun. Indeed, this element was first discovered in the sun, as its name implies. It was only recently discovered by Ramsay as occurring at all on the earth. We shall see that helium and radium are most closely associated. Wherever we find the one, we may reasonably expect the other. Helium, having been shown to exist in considerable quantities in the sun, the conclusion

[1] Phil. Mag., **5,** 591 (1903).

is highly probable that the sun also contains radium. The force of this argument will appear, and be the better appreciated, when the exact relation of helium and radium is taken up in a later chapter. The hypothesis of the radium origin of even a part of the solar heat is only an hypothesis, which it will remain for the future either to raise to the rank of a theory, or to disprove.

TERRESTRIAL HEAT PRODUCED BY RADIUM — BEARING ON THE CALCULATED AGE OF THE EARTH

We have seen that radium exists widely scattered over the surface of the earth. While only small quantities have been found in any one place, and while, in the opinion of the writer, for reasons already expressed, this is likely to continue to be the case, yet the total amount of radium in the earth may be very considerable. Indeed, there are reasons for supposing that beneath the surface of the earth there may be more radium than on the surface. The waters from certain springs, which probably come from considerable depths, contain radium. All of this radium is continually giving out heat.

Rutherford points out that the heat liberated by radium in the earth may have an appreciable effect on its age as usually calculated. In such calculations, starting with the earth as a molten mass, the main factors that are taken into account in addition to the original temperature are; the specific heat of the earth to determine how much heat it contains, and the conductivity of the crust of the earth for heat, to determine the rate at which the earth is losing heat. Given these data, the problem is to determine how long it would require the earth to cool from the condition of a molten mass to its present state.

In this calculation it is not assumed that there is any

large source of heat production going on within the earth itself. The hydration of the rocks, or the combination of the rocks with water as they cool, would liberate some heat, and this is taken into account. If, however, it should be shown that there is an appreciable quantity of radium in the earth, this would give off heat continuously, and in geological time the amount of heat from this source might be very considerable, relative to the total heat in the earth itself. This factor might vitiate the calculation of the age of the earth on the basis of the data that have been used, and produce a very considerable error in the result. The magnitude of the error would, of course, depend entirely upon the amount of radium in the earth.

THEORIES AS TO THE SOURCE OF THE HEAT PRODUCED BY RADIUM

Several theories have been advanced to account for the production of the heat that is continuously being liberated by radium. One is strictly analogous to the contraction theory of solar heat. The radium atom is contracting or shrinking up, and heat is therefore produced. This theory, which never met with much favor, is now untenable, for reasons that will appear as the subject develops.

The theory as to the origin of heat in the salts of radium, which accounts satisfactorily for the facts, and which is now generally accepted, is the following. We have seen that the α particles shot out by radium are incapable of penetrating any appreciable thickness of matter. They are all absorbed by thin screens. We have also seen that these particles have a mass at least twice that of the hydrogen atom, and possibly greater, and are shot out at very high velocities. These particles would, therefore, have large amounts of kinetic energy, and when they are stopped this

would be transformed into heat and would yield a large amount of it.

Take a pile of radium salt, the α particles shot off from the surface, not coming in contact with any of the salt above it, would escape at least a few centimetres into the air. But the α particles shot off from all of the radium at any appreciable distance beneath the surface of the salt would not escape, but would strike the solid salt above it and be stopped. The energy of motion of the α particle would thus become converted into heat. Since the mass of the α particle is considerable, and the velocity about one-tenth that of light, the kinetic energy would be great, and the amount of heat produced considerable.

This theory, which was proposed by Lodge,[1] to account for the heat liberated by radium, as produced by the stopping of the α particles in their flight, leaves still one question unanswered. How do the α particles acquire this great velocity with which they are shot off from the radium?

We can scarcely conceive of particles at rest in a molecule being shot off with such velocities. The particles in the molecule or atom of radium — the electrons — must be moving with very high velocities, and when a particle in its motion, gets beyond the control of the attractions of the remaining particles of the system, it flies off. This is true of the positively charged α particles, and also of the negatively charged β particles. The kinetic energy of these particles is then something inherent in the atom of radium. This we call *intrinsic energy*. It is obvious that this is the real source of the heat liberated by radium. The astonishing feature is the amount of the intrinsic energy contained in the atoms of radium.

[1] Nat., **67,** 511 (1903).

THREE REMARKABLE PROPERTIES OF RADIUM

We have thus far met with at least three properties possessed by radium, which are in the highest degree remarkable.

(1) We have seen that radium has the *power to charge itself electrically.*

(2) It also has the power to illuminate itself, or is, as we say, *self-luminous.*

(3) We have just seen that radium produces heat energy spontaneously, or *can warm itself.*

These three properties alone would suffice to place radium in a class by itself.

CHAPTER XII

EMANATION FROM RADIOACTIVE SUBSTANCES

WE have already seen that all radioactive substances give off α particles, which are positively charged, material bodies. All radioactive substances, with the exception of polonium, give off β particles, which are negative charges of electricity or electrons, having the same mass as the negative charges in the cathode ray, *i.e.*, about $\frac{1}{770}$ of the mass of the hydrogen ion in solution. All radioactive substances which give off β particles also give off γ rays. This includes all radioactive substances, with the exception of polonium. The γ rays are probably identical with the X-rays, except that they are far more penetrating.

We have also seen that radium gives out continuously large quantities of heat. Since this production of heat energy is due mainly to the α particles, it seems fair to assume that all radioactive substances that give off α particles, and this, as was just stated, includes them all, also give off heat energy. In the case of the weakly radioactive elements, such as uranium and thorium, the number of α particles given off is relatively small, and, therefore, the amount of heat energy given off by them is relatively slight. It may, indeed, be so slight as to escape detection.

In addition to these three kinds of radiations, and the heat, certain radioactive elements, such as thorium, radium, and actinium, give off what Rutherford calls an *emanation*. This substance, as we shall see, resembles in many respects

a gas. It can diffuse through porous bodies, can be condensed at low temperature, etc. It has in general the properties of the radioactive substances from which it was obtained.

DISCOVERY OF THE THORIUM EMANATION BY RUTHERFORD

The amount of the emanation given off even by radium is small, and for some time escaped detection. We owe its discovery in fact to the study of the radioactivity of thorium. It had been observed by Mme. Curie and others that the radioactivity of thorium was not constant when the thorium compound was placed in a vessel exposed to air currents. If the compound of thorium, on the other hand, was placed in a closed vessel, constant results could be obtained. It was found that the lack of constant results in open vessels was due to air currents. If a current of air was drawn through the closed vessel containing the thorium, inconstant results were again obtained. Rutherford [1] took up the study of the cause of this irregularity, and the result was the discovery of the emanation.

METHOD OF OBTAINING THE EMANATION

The emanation can be obtained from the salts of radium by simply heating them, or by dissolving them in water, when it is given off. It can be collected in a vessel like any other gas, and its properties studied. Before taking up its general physical and chemical properties, one property especially will be discussed in some detail, since it practically demonstrates the gaseous nature of this substance. The emanation can be condensed at low temperatures, like an ordinary gas, into a liquid. [2]

[1] Phil. Mag., **49,** 1 (1900).
[2] Rutherford and Soddy: Phil. Mag., **5,** 561 (1903).

If hydrogen is allowed to bubble through a solution of a radium salt, and is then passed through a U-tube surrounded by liquid air, the emanation condenses in the tube.   Similar results are obtained if the products expelled by heating a radium salt are passed through a U-tube dipped in liquid air.

If only a small amount of the radium salt is available, the condensation of the emanation is shown by the fact that the escaping hydrogen is either not radioactive at all, or only slightly so; while the emanation is extremely radioactive.   If a larger amount of the emanation is obtainable, its presence in the cold glass tube can be seen; not by producing under ordinary conditions a visible amount of liquid, but by a fluorescence in the air in the cold tube, and also by rendering the walls of the tube brilliantly phosphorescent.

By a modification of the above-described experiment, it is possible to determine the temperature at which the emanation condenses or boils.   A mixture of the emanation and a neutral gas is passed through a tube cooled down below the temperature at which the emanation condenses.   When the emanation was all condensed, the escaping gas, hydrogen, oxygen, nitrogen, or air showed no radioactivity when tested by the electrical method.   After all the emanation had been condensed, a current of neutral gas, say hydrogen, was passed through the tube containing the emanation. The temperature in the condensing tube gradually rose, due to the presence of the warmer gas, and when the boiling-point of the emanation was reached and a little of it was volatilized, its radioactivity manifested itself in deflecting the electrometer with which the vessel into which the emanation passed was connected.   When this took place, the temperature in the condensing vessel was read by means of a copper resistance thermometer that had been previously calibrated.

The average result from a number of experiments showed that the emanation condenses at -152 degrees centigrade. This point was fairly sharply determined by the fact that the ionization or conductivity of the gas, into which the escaping emanation passed, reached a maximum shortly after the emanation began to volatilize, and when the temperature had been raised only a very slight amount.

The emanation thus condenses to a liquid just like a gas, and like a gas has a perfectly definite boiling-point.

AMOUNT OF THE EMANATION

The amount of the emanation obtainable even from an appreciable quantity of radium is very small indeed. If the emanation that can be obtained from a tenth of a gram of radium chloride or bromide is condensed in a glass tube as previously described, no liquid or even mist will be seen in any part of the tube. All that will be seen is a phosphorescence on the walls of the tube, and this may extend through the neutral gas within the tube.

Sir William Ramsay and Soddy have measured approximately the volume of the emanation obtainable from a given quantity of the radium salt. The emanation was collected in a capillary tube which had been graduated, and measured.

From sixty milligrams of radium bromide they obtained 0.124 cubic millimetre of the gas. This volume *decreased rapidly with time*, and we shall learn that this is a very important fact.

NATURE OF THE EMANATION

In studying the properties of the emanation we encounter the great difficulty, which at present is insurmountable, that it cannot be obtained in appreciable quantity. This is especially true of the emanation from thorium, as might

be expected from the small radioactivity of this element. We have just seen that the emanation from radium disappears, or "decays," as it is said, quite rapidly. This is especially true of the emanation from thorium, which is not only infinitesimal in quantity, but disappears or decays in a few minutes. The emanation from radium, however, does not entirely decay for a number of days.

The emanation itself is unaffected by an electrostatic field, and is, therefore, not charged. It can, however, produce phosphorescence in certain substances.

After having shown that the emanation has many of the properties of gases, and is certainly material in nature, attempts were made by Rutherford to identify it with some of the known substances. Its chemistry was studied as far as possible with the small quantity available. It was subjected to *very high temperatures*, but was unaffected by this treatment. Then it was passed through a platinum tube heated as highly as the nature of the tube would permit. It was also passed over heated platinum black, and escaped in both cases without change. In the above experiments the emanation was mixed with air. It was then mixed with hydrogen and passed over red-hot, magnesium powder, and also over red-hot palladium, but it was still unaffected.

Ramsay sparked a mixture of the emanation with oxygen, for a long time, in the presence of an alkali, and also heated it in the presence of magnesia lime, but the emanation was unchanged. The emanation thus differs from all known forms of matter, except argon and the other members of this group of elements, which are characterized by their chemical inertness.

While we do not know, even at present, very much about the chemistry of the emanation, it seems safe to conclude that if it is an element it belongs to that inactive group of

chemical elements of which argon was the first member to be discovered. Even if it should be shown *not* to be elementary, it nevertheless resembles in its chemical properties the elements of this group.

Some light has been thrown on the *physical properties* of the emanation, notwithstanding the fact that it has been obtained only in such small quantities.

DIFFUSION OF THE EMANATION — APPROXIMATE DETERMINATION OF ITS MOLECULAR WEIGHT

It is well known that gases diffuse with very different velocities. If we allow gases of different densities to diffuse into any gas, say the atmospheric air, we shall find not only that they will diffuse with very different velocities, but a regularity will manifest itself. The lighter gases will diffuse more rapidly than the heavier ones.

If we work quantitatively, we shall find a very simple relation between the densities or the molecular weights of gases, and the rates at which they will diffuse.

GASES DIFFUSE WITH VELOCITIES THAT ARE INVERSELY PROPORTIONAL TO THE SQUARE ROOTS OF THEIR DENSITIES

This generalization, known from its discoverer as the law of Graham, is comprehensive, holding for all well-known gases.

Upon the basis of this generalization, Rutherford and Miss Brooks [1] have attempted to determine approximately the molecular weight of the emanation from radioactive substances, notwithstanding the fact that the largest amount of the emanation thus far obtained is scarcely weighable even with the most refined chemical balance.

[1] Chem. News, **85**, 196 (1902).

They allowed the emanation to diffuse from one end of a tube into the other, and measured the change in the conductivity of the air in the tube.

From the data thus obtainable the diffusion coefficient of radium could easily be calculated.

The experiments which, on the whole, were the most satisfactory and probably the most accurate, gave a diffusion coefficient which was close to 0.07.

If we compare this coefficient with the diffusion coefficients of vapors whose molecular weights are known, we find that it comes close to the coefficient for ether, which has the value of 0.077, and the molecular weight of ether is 74. The molecular weight of the emanation from radium must, therefore, be close to 74. All things considered, Rutherford seems to think that the molecular weight of the radium emanation is not far from 100. The emanation from thorium was shown to have practically the same molecular weight as the emanation from radium.

Since the above determinations of the molecular weight of the radium emanation were made by Rutherford and Miss Brooks, new determinations have been carried out by Makower,[1] working with J. J. Thomson.

Radium bromide was dissolved in water and the emanation removed by passing air through the solution. The mixture of air and the emanation was collected over mercury in one arm of a glass vessel resembling a Hempel burette, which was closed at the top by a porous plug. This vessel, known as the diffusion vessel, was connected with a cylindrical brass vessel. Into the centre of this brass cylinder a brass rod was introduced, so as to be insulated from the walls of the vessel. By means of a storage battery of two hundred cells, a difference in potential of about four

[1] Phil. Mag., **9,** 56 (1905).

hundred volts was established between the brass rod and
the walls of the box. A known volume of the mixture of
air and the emanation was introduced from the diffusion
vessel into the brass cylinder, and the conductivity of the
gases in the cylinder determined. As soon as the conduc-
tivity had been determined, the emanation was quickly
pumped out of the cylinder, so as to minimize the amount
of the "induced radioactivity" on the walls of the vessel,
which quickly decayed.

The mixture of air and the emanation now gradually
diffused out of the diffusion vessel, through the porous plug.
From time to time fresh quantities of the mixture were
driven over from the diffusion vessel into the brass cylinder,
and its conductivity determined. As more and more of
the emanation diffused out through the porous plug in the
top of one arm of the diffusion vessel, the conductivity of
the mixture remaining in the vessel became less and less,
as was shown by testing the conductivity at short intervals,
by the method already described. In this way it was not
difficult to determine the rate at which the emanation dif-
fused out through the porous plug.

To determine the molecular weight of the emanation, it
was necessary to compare its rate of diffusion with that of
gases whose molecular weights were known, diffusing
through the same porous plug. The gases employed were
oxygen, hydrogen, carbon dioxide, and sulphur dioxide.
The gas was introduced into the diffusion vessel and allowed
to diffuse out into the atmosphere. Knowing the molecu-
lar weights of the gases, the rates at which they diffuse
through the given porous plug, and the rate at which the
emanation diffuses through the same plug, we can calculate
the molecular weight of the emanation from Graham's
law.

The results showed a molecular weight for the radium emanation ranging from 85.5 to 99. On the assumption that the radium emanation is a monatomic gas, Makower points out that this result would give it a place in the Periodic System in the fluorine group between molybdenum and ruthenium.

The molecular weight of the emanation from thorium was found to be slightly smaller than that from radium.

These results show that the molecular weight of the emanation is very nearly one hundred, as Rutherford had supposed.

CHAPTER XIII

HELIUM PRODUCED FROM THE EMANATION

WE have seen that the emanation is material, and has many of the properties of an ordinary gas. We have also seen that when the emanation is present in the radium, the latter gives out α, β and γ radiations. The question arises whether the emanation gives out all three types of rays, or only certain special types, or does it give out any radiation at all?

This was tested by Rutherford and Soddy [1] in the following way. The thorium, containing the emanation, was placed in a metal box, having a hole in the top that was covered with a plate of mica. The radiation from the emanation that passed through the mica was tested by its power to ionize the gas above it. When a thin metal disk was interposed in the path of the radiation, most of the radiation was cut off. This showed that at least most of the radiation consisted of α rays. No evidence was obtained that any β rays were present.

In the case of the emanation from radium, the test as to its nature was made as follows: The emanation was introduced into a copper tube, whose walls were thick enough to cut off all the α rays. No β or γ rays were given out by the emanation itself.

The emanation gives out, then, only one type of radiation, and that is the α type. No β or γ rays come from the emanation either from thorium or radium. It will be re-

[1] Phil. Mag., **5**, 445 (1903).

membered that the α rays are composed of positively charged particles, having a mass about twice that of the hydrogen atom, and moving with a velocity which is about one-tenth that of light. It will also be recalled that it is the α particles that have most of the energy given off by radioactive substances, since they have appreciable mass and very high velocity. The α rays are the chief agents that ionize a gas subjected to radioactive substances, and are the most important radiations given off by such substances.

Having found that the emanation gives off α particles, the next question is, do *all* the α particles shot off from radium come from the emanation contained in it, or has deemanated radium any power to produce α rays? This can easily be answered. When all of the emanation is removed from the radium salt by heating, the remaining deemanated radium also has some power to give out α particles.

Rutherford studied the effect of *low temperature* on the rate at which the emanation was produced. He found that the emanating power of thoria was diminished to about one-tenth at the temperature of solid carbon dioxide.

M. Curie found that the emanating power of radium compounds was much increased by dissolving them in water. The meaning of some of these empirical facts will appear when we come to study the nature of the changes that are taking place in radioactive substances.

RECOVERY OF EMANATING POWER

When thorium or radium compounds are subjected to a high temperature they become deemanated, or lose most of their emanating power. They, however, regain this power on standing, more and more of the emanation being produced.

DECAY OF THE EMANATION

If we study the emanation, we find that the activity of the emanation rapidly diminishes. The activity of the emanation obtained from thorium *decreases to one-half its initial value in about one minute*, and almost entirely vanishes in a very few minutes.

The activity of the radium emanation is, however, more persistent. The most careful work on this problem is undoubtedly that of Rutherford and Soddy. A mixture of the emanation with air was preserved over mercury, and samples removed and examined from time to time. They found that the activity of the emanation from radium fell to half the initial value in 3.7 days.

The *rate of decay of the emanation seems to be independent of the conditions* to which the emanation is subjected. Even *high temperatures have no effect on the rate*, and when the emanation is condensed to a liquid at low temperatures, the decay goes on at the same rate.

HEAT EVOLVED BY THE EMANATION

We have discussed at some length in an earlier chapter the remarkable heat-producing power of radium. We have seen that the amount of heat liberated by radium is one of the most surprising facts in physical science.

We have now studied in some detail the unique substance which is being constantly produced and given off by radioactive substances, known as the emanation. It is extremely radioactive considering its quantity. Indeed, much of the radioactivity of radium and thorium can be referred to the emanation produced by and contained in them.

We would naturally ask, does the emanation have anything to do with the enormous production of heat that is taking place in radium salts, and if so, what?

The answer to this question we owe to Rutherford and Barnes.[1] They worked with only thirty milligrams of the bromide of radium and determined the total heat emission of this substance.

They then distilled off the emanation and condensed it in a tube surrounded by liquid air. This tube was sealed up while immersed in the refrigerating agent. The heat that was liberated by the emanation in the tube was then measured from time to time, and also the heat that was liberated by the radium bromide from which the emanation had been distilled. The sum of the heat liberated by the emanation, plus that liberated by the bromide from which the emanation had been obtained, was always equal to the total amount of heat set free from the original bromide.

When the emanation was giving out a maximum amount of heat, the surprising fact was established that *from seventy to seventy-five per cent. of the total heat given out by radium salts comes from the emanation contained in them.*

This fact is even more wonderful than the discovery that small amounts of radium salts can give off such large amounts of heat. We have now traced the source of most of this heat to the almost infinitesimal quantity of emanation contained in such small amounts of the salts of radium that are at present at our disposal.

HELIUM PRODUCED FROM THE EMANATION

We have already encountered a number of remarkable and surprising facts in connection with the radioactive elements and the emanation produced by them. Perhaps the most remarkable still remains to be considered. We have seen that the activity of the emanation gradually

[1] Phil. Mag., 7, 202 (1904).

decays and finally becomes zero. This necessitates the conclusion that some fundamental change is going on in the emanation itself.

A number of questions arise in this connection. Especially prominent is this one: If the emanation is undergoing decomposition, into what does it decompose? What is left in a tube containing the emanation after the emanation has ceased to be radioactive?

If we go back to pitchblende — the source of most of our radium — we find such a large number of things, that it would appear to be difficult to say that any one of them was a product of the decomposition of the emanation from the radium contained in this mineral. We, however, find most of these substances occurring in other associations somewhere in nature where no radium is present, and they, therefore, could not be the final product of the decomposition of the radium emanation.

If we examine the radioactive minerals closely we shall see, however, that they contain one substance, of which the above remark is, at best, only partially true. This is the element helium.

This element, as has already been pointed out, was first discovered spectroscopically in the sun by Lockyer. It was first discovered among the terrestrial elements by Ramsay. This discovery has an interesting history. Ramsay was working with Lord Rayleigh on argon, and had studied its properties, and especially its chemical inertness. In this connection it occurred to him to examine the inert gas previously obtained from the mineral cleveite, to see whether it was not argon. He examined it spectroscopically and found a prominent yellow line near the sodium line, which he could not identify as coincident with that of any known terrestrial element. However, on comparing

it with the line discovered by Lockyer in the sun, Ramsay found that the two were identical.

Helium was thus shown to exist among the terrestrial elements.

It should further be pointed out that helium, as far as it occurs at all in minerals, is only to be found in the radio-active minerals. Helium is also found in the waters of certain springs, but probably comes from radioactive minerals which are at some depth below the surface of the earth.

Taking these facts into account, and also the chemical properties of the emanation from thorium and radium, Rutherford and Soddy [1] suggested that the emanation on decomposing might yield some inert element of the type of those in the argon family.

On account of his ability and experience in working with small quantities of gases, Sir William Ramsay [2] undertook the study of the nature of the emanation, in conjunction with Mr. Soddy.

They dissolved from 20 to 30 milligrams of radium bromide in water, and collected the emanation in a sparking tube. The sparking tube was connected with a U-tube which was surrounded by liquid air. This condensed any carbon dioxide that was present in the emanation as an impurity, and also the emanation. If any helium was produced from the emanation, this would not be condensed by the liquid air, since helium is the one gas that has not been liquefied by any means, even up to the present time.

When the spectrum of this tube was taken, a bright yellow line made its appearance, which was not far removed from the sodium line; but even with a small spectroscope could

[1] Phil. Mag., **4**, 581 (1902).
[2] Nat., **68**, 246 and 354 (1903).

be seen *not to be identical with it.* A careful measurement of *this line showed it to be identical with the D_3 line of helium.* This preliminary experiment with its remarkable result, led to further very careful work on the problem. The emanation from 50 milligrams of radium bromide was collected in a U-tube by driving it over with oxygen, and then condensed in the tube by means of liquid air. It was then transferred to a Plücker sparking tube, and the spectrum taken. *At first there were no helium lines present,* but a new spectrum, presumably that of the emanation itself, made its appearance. *In a few days the original spectrum disappeared and the spectrum of helium came out sharply.*

Thus was observed for the first time in the history of science the formation or production of a chemical element. Whether it comes directly from another definite chemical element is not certain. It has not been shown, although it is highly probable, that the emanation is an inert chemical element. It is, however, certain that helium is thus spontaneously produced from a chemical element — radium — as one of its decomposition products.

THIS IS NOT A TRANSMUTATION OF THE ELEMENTS

Since the discovery referred to above was made, there has been so much written about the "Transmutation of the elements having been effected," the "Dream of the alchemist realized," etc., that a word of warning seems highly desirable.

From some of the statements on this subject that have appeared, any one unfamiliar with the facts might conclude that we are now able to effect the reciprocal transformation of practically any elementary substances almost *ad libitum. We are no more able to effect such transforma-*

tions to-day than was possible a thousand years ago, nor has such a transformation ever been effected by any one.

It appears to the writer to be one thing to discover an *unstable* system in nature, even if it corresponds to our definition of chemical element, which is *spontaneously* undergoing changes that are *largely unaffected even by the most extreme artificial conditions* that we can bring to bear upon it, and giving rise to another elementary substance as one of its decomposition products; and an entirely different thing to *effect the transformation* of a *stable element into another elementary substance by purely artificial means*.

By showing that helium is one of the decomposition products of radium, it has been shown that the process first described does actually take place, at least in the case of one substance. The second transformation still remains to be effected.

In calling attention to the above distinction, no attempt is made to belittle the magnificence of the discovery of the spontaneous formation of helium from radium, which, when we consider the difficulties involved in working with such small quantities of substances, is to be placed among the great achievements of modern science, and could not have been accomplished by a man of less experimental skill than that possessed by Sir William Ramsay.

FURTHER EXPERIMENTS ON THE PRODUCTION OF HELIUM FROM RADIUM

It is obvious that such an epoch-making discovery as that described above would be subjected to the closest scrutiny, even when announced by such a distinguished authority as Ramsay. The first question that would occur to any one is this, Could the helium that appeared with the emanation have been *occluded* in the radium salt, and set

free when the emanation was separated from the salt? This is, of course, a fair question to ask, but the answer was furnished by Ramsay himself. The salt of radium was heated in contact with a vacuum pump for a long time, so that any gas occluded in the radium salt must have been liberated. When the salt of radium thus treated was allowed to stand until the emanation was formed, and this emanation then driven off and collected in a sparking tube, the presence of helium lines manifested themselves after a few days.

One fact, as has doubtless already been noted, in connection with the appearance of helium lines in the emanation, of itself argues strongly against any helium having been occluded in the radium salt, and then set free when the salt was dissolved in water. The emanation freshly distilled from the radium salt showed no trace of the helium spectrum. The spectrum of helium appeared only after the emanation had stood for some time. If the helium was really occluded in the radium salt, its spectrum should have manifested itself as soon as it was driven over into the Plücker tube. The fact that it did not, but appeared after the tube containing the emanation had stood for a time, is a strong argument in favor of the helium having been produced by some change taking place in the emanation itself.

An even more crucial test, if possible, of the occlusion theory to account for the helium was made by Dewar, Curie and Deslandres.[1] Four hundred milligrams of radium bromide were dried and placed in a small glass vessel. This was connected with a small Geissler tube, and the whole system exhausted. The degree of the exhaustion was registered on a manometer. During the three months that the bro-

[1] Compt. rend., **138**, 190 (1904).

mide was contained in the exhausted glass vessel, gas was continually being given off. This gas was found spectroscopically to be hydrogen, produced probably by the decomposition of traces of moisture in the salt by the radium.

The radium bromide was now transferred to a small quartz vessel, which was then exhausted. It was heated until the bromide fused. The gases that were given off during the heating were passed through U-tubes plunged in liquid air. This condensed the emanation and any of the less volatile gases. During the heating some nitrogen gas was given off, having been occluded in the salt. The quartz vessel containing the radium bromide, from which all occluded gases had now obviously been removed, was sealed up by means of an oxyhydrogen blowpipe.

After the tube had been closed twenty days, Deslandres studied its contents spectroscopically. The gas in the tube gave now the entire spectrum of helium.

The result of this investigation was to confirm in every respect the conclusion previously reached by Ramsay. Helium is formed as the result of some change going on in the radium, or in the emanation from the radium.

RELATION BETWEEN THE EMANATION AND HELIUM

Having shown that the helium which appeared in the sparking tube along with the emanation was not occluded in the salt of radium from which the emanation was obtained, the next question that was raised is, What relation does the helium bear to the emanation from which it is produced? It was easy to show in a number of ways that the emanation itself is not helium. The spectrum that first appeared when the emanation was collected in the sparking tube was not that of helium at all, but was an entirely new spectrum, not corresponding to that of any known substance.

As we have seen, the helium lines appeared only after the emanation had stood for a time. Again, the emanation is radioactive, giving off α particles. Helium does not give off such particles, and, indeed, is not radioactive at all.

Further, the emanation is condensed by passing through a tube surrounded by liquid air, while helium cannot be condensed to a liquid even at the temperature of liquid hydrogen — helium being the one gas that has thus far not been converted into a liquid.

Helium is the lightest gas known next to hydrogen, its atomic weight being four, and the molecule monatomic. The emanation, on the other hand, has a molecular weight of about 100, as we have seen from diffusion experiments.

The emanation is, then, fundamentally different from helium in all of its properties, and yet helium is produced from it as is shown by spectrum analysis. A theory to account for the production of helium from the emanation should be mentioned, even if it is insufficient, as it will be encountered in the literature.

It has been suggested that radium is not a chemical element, but a compound of helium with some presumably unknown element. The helium that was produced from radium was the result of the breaking down of this compound. There are a number of reasons why this theory is insufficient. In the first place, radium has all the properties of a chemical element — including a well-defined spectrum. Again, such a theory would not account for the radioactivity of radium, nor for the amount of heat energy that is being liberated by it.

To explain the properties of this remarkable substance, a theory along entirely new lines, as we shall see, is necessary.

CHAPTER XIV

Induced Radioactivity

It was observed by the Curies[1] that substances in general became radioactive in the presence of radium which is very radioactive. This was the case when the substances in question were removed from any dust of the radium salt. This phenomenon was named by the Curies *induced radioactivity*.

The property of rendering substances in the neighborhood radioactive is not limited to radium. Rutherford[2] found that salts of thorium have the same property, and Debierne showed that actinium had the power of inducing radioactivity to a very high degree.

The Curies[3] studied this property of radioactive substances in the following manner. They used a closed vessel into which the radioactive substance, and the substances on which radioactivity was to be induced, were placed. Under these conditions, as would be expected, more marked effects were produced as well as more regular results obtained.

The active substance was placed in a small glass vessel open at the top, which was suspended in the centre of an inclosed space. Pieces of such widely different substances as glass, hard rubber, paraffin wax, aluminium, copper and lead, having, however, equal surfaces, were inclosed

[1] Ann. Chim. Phys. [7] 30, 289 (1903).
[2] Phil. Mag. 49, 161 (1900).
[3] Ann. Chim. Phys. [7] 30, 211 (1903).

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in the space along with the radium salt. It was found
that *all* of these substances became radioactive, and were
radioactive to just exactly the same extent when the free sur-
faces were the same.

To test whether the induced radioactivity was caused by
the radiations falling directly upon the plate, a thick lead
screen was placed in the inclosed space, to one side of the
vessel containing the radium salt; and behind this screen
was placed a piece of metal, having the same surface area
as the other objects in the inclosed space. It was found
that this substance, thus protected from the radiations
given out by the active salt, became just as radioactive as
the other substances having the same surface, exposed to
the direct action of the radiations.

The further interesting experiment was tried, of closing
the vessel containing the radioactive substance. When
the vessel was closed it was found that none of the sub-
stances became radioactive. By closing the vessel, then,
the power of the radioactive substance to induce radio-
activity in other bodies was lost. It was found that
the induced activity was more intense and more regular
if the active substance was in solution than if it was in the
solid state.

Water itself becomes radioactive if allowed to stand in a
closed vessel along with some salt of radium.

Certain substances, such as glass, paper, and especially
zinc sulphide, became phosphorescent under the same con-
ditions as those to which the above-named objects were
subjected. When the induced radioactivity of these phos-
phorescent substances is measured, it is found to be the
same as the induced radioactivity of other non-phosphores-
cent substances, subjected to the same exciting cause.
The production of phosphorescence in such bodies, then,

neither increases nor diminishes the excited radioactivity produced in them.

The Curies also established the following facts. If a given object is exposed to a radioactive body in a closed vessel, the induced radioactivity in the object increases with the time of the exposure, until a certain definite, maximum value is reached. This maximum value is independent of the nature of the gas that fills the vessel containing the radioactive substance, and the material on which radioactivity is to be induced; and is dependent, for a given arrangement of the apparatus, only upon the amount of the radioactive substance present in solution in the confined space.

INDUCED RADIOACTIVITY PRODUCED BY THE EMANATION

It has already been shown that the induced activity is not due to the radiations from the radioactive bodies, since, when the radiations are cut off from an object by a thick lead screen, this object still becomes radioactive if contained in a closed vessel with the radioactive substance. It has also been shown that if the vessel containing the radioactive material is completely closed, the radioactive substance in the vessel does not excite radioactivity in objects around it.

This would strongly indicate that the excitant of radioactivity must be something analogous in properties to a gas, since it is so readily cut off, and since it can pass around a screen and induce radioactivity in an object placed behind the screen just as if the screen was not present.

The only substance given off from such radioactive bodies as thorium, actinium, and radium, which has the properties of a gas, is the emanation; and we should expect that the induced or excited radioactivity was caused by the emanation.

This supposition was greatly strengthened by the fact that only those elements that produce an emanation have the power of exciting radioactivity in non-radioactive substances.

This view that the induced radioactivity was caused by the emanation we owe to Rutherford, who furnished a number of lines of evidence for his theory. He showed that when the emanation from radium was cut off, the radium lost its power of inducing radioactivity in other bodies. He also showed that the *induced radioactivity was proportional to the emanating power of the substance inducing it*. The amount of the emanation present was measured by its power to ionize a gas and thus render it a conductor. When this was compared at different intervals with the radioactivity produced, it was found that the two are proportional, to within the limits of experimental error.

INDUCED RADIOACTIVITY UNDERGOES DECAY

We have seen that the radioactivity of the emanation itself undergoes decay. Since the emanation is the cause of the induced radioactivity, we should naturally expect that the induced radioactivity itself would decay with time, and such is the fact.

If a body is subjected for a considerable time to the emanation from thorium, and then removed, the excited radioactivity decays regularly, reaching half of its initial value, according to Rutherford, in about eleven hours. The rate of the decay of the induced radioactivity, like so many other properties of radioactive substances, is apparently independent of many of the conditions to which it is subjected.

The induced radioactivity produced by the emanation from radium decayed much more rapidly than that pro-

duced by the emanation from thorium. It undergoes changes somewhat analogous to those already considered, decaying to half-value in a few minutes.

We should naturally like to know whether this decay continues to the limit. Do the bodies once rendered radioactive by the emanation from naturally radioactive substances quickly become completely non-radioactive again? This information has been furnished, at least in part, by the Curies. They found that the induced activity produced by radium diminished to half-value in a few minutes, but a small, residual activity persisted for almost an indefinite time.

INDUCED RADIOACTIVITY DUE TO THE DEPOSIT OF RADIO-ACTIVE MATTER

The relation between induced radioactivity and the emanation from radioactive substances has been developed, and it has been shown that the latter is the cause of the former. This, however, but raises the question, how does the emanation render objects exposed to it temporarily radioactive? To answer this question we must study closely the property of induced radioactivity. If a thorium or radium salt is placed in a closed vessel, all objects in the same vessel, whatever their nature, are rendered radioactive. If, however, a negative electrode is introduced into the vessel, *all* the excited radioactivity is confined to this electrode. A convenient method of performing this experiment is to introduce the radioactive salt into a metal vessel which is connected with the positive pole of a battery. A metal wire is introduced into the middle of the vessel, passing through an insulating stopper. This wire is made the *negative pole* of the battery. Under these conditions, the wire is the *only object* in the vessel that is rendered radioactive, and its induced radioactivity may, according

to Rutherford, become many thousand times greater than the natural activity of the thorium salt which induced the activity in the negative electrode.

It is difficult to account for this fact, together with the fact that the emanation is the cause of all the induced radio-activity, on any other ground than that the *induced radio-activity is produced by a deposit of radioactive matter upon objects placed in the neighborhood of naturally radioactive substances.*

This theory would explain the above and correlated facts.

To propose a theory that explains all the known facts and predicts new ones is one thing, but to show that this is the only suggestion that will account for these facts is quite a different matter. Further, the value of a theory or generalization is to be tested rather by its ability to predict new and undiscovered facts, and then have the predictions verified by experiments, than simply to account for what is already known.

If the induced radioactivity is due to the deposition of radioactive matter upon non-radioactive substances, then this matter would have definite properties. We ought to be able to remove it mechanically from the object upon which it was deposited, etc.

We shall now see that the cause of the induced radio-activity can be removed mechanically and otherwise from objects upon which it has been deposited, and that its properties have already been studied in some detail.

PROPERTIES OF THE RADIOACTIVE MATTER DEPOSITED BY THE EMANATION FROM RADIOACTIVE SUBSTANCES

The properties of the active matter deposited by the emanation from thorium have been studied by von Lerch [1]

[1] Ann. d. Phys., **12**, 745 (1903).

and by Rutherford.[1] The active matter was allowed to deposit upon platinum, and its solubility in different solvents then determined by measuring the decrease in the induced radioactivity of the platinum. This active matter was insoluble in such organic solvents as ether and alcohol. It was dissolved by hydrochloric acid, and the solution was radioactive. The radioactivity of this solution was greatly diminished by causing a precipitate to be thrown down from it. Thus, if barium chloride was added to the hydrochloric acid solution, and the barium thrown down as sulphate, most of the radioactive matter was carried down by the precipitate which was strongly radioactive.

If a piece of magnesium was exposed to the emanation from thorium until it became highly radioactive, and then dissolved in hydrochloric acid, the magnesium when precipitated as carbonate or phosphate carried down with it the radioactive matter.

Rutherford showed that the active matter can be removed from an object upon which it has been deposited, purely mechanically. If a piece of platinum wire has been rendered highly radioactive by exposing it for some time to the emanation from thorium, and is then rubbed with a piece of sand-paper, nearly all of the radioactive matter can be removed from the platinum. The sand-paper, in turn, becomes radioactive.

We know less about the properties of the radioactive matter deposited by the emanation from radium, since, as we have seen, this *decays* much more rapidly than the deposits from the emanation given off by salts of thorium. It has, however, been shown that the radioactive matter from radium differs at least in its solubility from the radioactive matter deposited from thorium.

Phys. Zeit., **3**, 254 (1902).

EMANATION X

The above facts suffice to show that induced radioactivity is caused by the *deposit upon the non-radioactive substance of a radioactive form of matter*, which can be removed from the substance either mechanically or chemically, and which has definite chemical and physical properties of its own. This radioactive deposit has been termed by Rutherford *emanation X.* Another name was given to it later, as we shall see. The amount of such radioactive matter that is deposited is extremely small. This is what we should expect, since we have learned that the amount of the emanation itself, given off by the most active substances, radium and actinium, is almost infinitesimal. Rutherford points out that no matter how long a piece of metal is exposed to the emanation, the amount of radioactive matter deposited is *too small to be detected, even with the most refined balance.*

Here is then another remarkable fact added to that long list of such facts that have been brought to light as the result of the discovery and study of radioactive phenomena. Certain radioactive substances give off almost an infinitesimal quantity of a kind of matter that is analogous to a gas, and which has properties literally undreamed of by men of science. This minute quantity of substance manifests most of the radioactivity shown by the natural radioactive substance from which it came. It produces a chemical element helium as one of its decomposition products, and perhaps most remarkable of all is the *amount of energy* that it can give out in the form of heat. It was justly regarded as one of the most surprising facts known to science, when the Curies discovered that salts of radium themselves gave out heat in such quantity that a piece of radium would melt its own weight of ice every hour.

This discovery dwindles into insignificance in comparison with that made by Rutherford, that about three-fourths of this heat comes from something that exists in the radium salt in relatively infinitesimal quantity, and which is continually decaying and being manufactured by the radium — the *emanation*. It is perhaps no great cause for wonder that such a discovery should have raised questions even in connection with such a fundamental generalization as that of the conservation of energy.

We now find that the emanation in decaying yields a product, which must exist in still smaller quantity than the emanation itself, and which has the power of rendering inactive substances on which it is deposited *strongly radioactive*. This induced or excited radioactivity as it is termed also undergoes decay, showing that the radioactive matter deposited by the emanation undergoes still further changes.

Some of these have already been studied by Rutherford.

FACTS THAT MUST BE TAKEN INTO ACCOUNT IN DEALING WITH THE DECAY OF INDUCED OR EXCITED RADIO- ACTIVITY

In studying the transformations that are undergone by the radioactive matter deposited by the emanation, let us first turn to the facts that have been brought to light by Rutherford, and clearly stated by him in his Bakerian lecture [1] before the Royal Society.[2]

To simplify the matter, we shall deal with the transformations in detail only in the case of radium. The induced radioactivity produced by radium undergoes decay, and at the same time gives off α, β, and γ particles. If we measure the decay of the excited radioactivity by means of

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[1] Phil. Trans., A, **204,** 169 (1904).
[2] See also Phil. Mag., **8,** 636 (1904).

the α rays, we obtain a different result from that arrived at if we measure the decay by means of the β or γ rays. The decay was measured by means of the α rays, also by means of the β rays, and finally by means of the γ rays.

Some of the results that were obtained in the case of radium are the following: After the rod was exposed to the radium emanation, the activity as measured by the α radiation *decreased at first comparatively rapidly.* The decay then progressed slowly, finally becoming almost zero.

If the rate of decay of the induced activity is measured by the β *rays*, quite different results are obtained. The decay as measured by the β radiation after the first ten or fifteen minutes resembles the decay as measured by the α radiation. The decay as measured by the α radiation diminishes very rapidly for the first fifteen minutes. This is not the case when the rate of decay is measured by the β radiation.

When the rate of decay is measured by the γ radiation, results are found which are exactly similar to those obtained with the β radiations. This is just what we should expect from the relation that we have already learned exists between the β and γ rays.

INTERPRETATION OF THESE FACTS

The following interpretation of the above facts has been given by Rutherford: The rapid initial decrease in the radioactivity, as measured by the α rays, is due to a change taking place that gives rise to the α rays. If we examine the activity as measured by the β ray during this period, we find the absence of any sudden drop during this initial time. This shows that the first transformation, which takes place largely during the first three minutes, does not give out β rays, otherwise the activity as measured by the β rays would decrease rapidly during this period.

We will term the active matter deposited by the emana-
tion, not emanation X, as we have hitherto done, but *radium
A*. Radium A gives out α particles only, and quickly under-
goes a transformation into *radium B*.

A study of the rate of decay, as measured by α, β, and γ
rays respectively, leads to the conclusion that a second
transformation goes on, in which no radiation is given out.
In this second change, radium B passes over into *radium
C*. By the same general line of reasoning as that employed
above, we must conclude that radium C passes over into
radium D, giving out α, β, and γ radiations during the
transformation.

Rutherford thinks he has detected a still further trans-
formation of radium D into *radium E*, no rays being given
out. Radium E gives off β and γ particles and passes over
into something the nature of which will be discussed in the
last chapter.

In a manner similar to the above, it has been made highly
probable that the emanation from thorium gives rise to a
radioactive deposit — thorium A, which undergoes at least
two transformations, giving thorium B and thorium C.

Uranium does not yield an emanation, but uranium X
apparently breaks down at once into the final product.

Actinium yields an emanation, which decomposes in at
least three stages, giving actinium A, B, and C.

The chemical nature of such products as those just de-
scribed is entirely unknown, and will remain so until they
can be obtained in sufficient quantity to be studied at least
by the more refined chemical methods.

CHAPTER XV

PRODUCTION OF RADIOACTIVE MATTER

CONTINUOUS FORMATION OF RADIOACTIVE MATTER IN URANIUM

WE have learned that thorium and radium from which the emanation has been removed have lost most of their radioactivity. We have seen that the emanation loses its activity, but what is more important in the present connection, the deemanated substance *regains its radioactivity on standing*. Further, when all the emanation has been driven out from a radioactive substance and the deemanated body has regained its radioactivity on standing for a time, more of the emanation can then be removed from this same material.

These facts can best be interpreted by assuming that some change is continuously going on in the radioactive substances, *which gives rise to the emanation* and restores the radioactivity.

In connection with the changes taking place in radioactive substances a most important discovery was made by Sir William Crookes.[1] He found that a very active constituent could be separated from uranium by chemical means, and that the remaining uranium was not appreciably radioactive.

If to a solution of a uranium salt a solution of ammonium carbonate is added, the uranium is precipitated. If an

[1] Roy. Soc. Proceed., **66**, 409 (1900).

excess of the ammonium carbonate is added the precipitate dissolves in this reagent.   There, however, remains a small, light brown residue that does *not* dissolve when an excess of ammonium carbonate is added.   This residue can readily be filtered off from the solution, and was found to be highly radioactive, as compared with uranium itself.   This residue was called by Crookes *uranium X*, and was given the symbol UrX.

RECOVERY OF ACTIVITY BY URANIUM, AND DECAY OF ACTIVITY IN URANIUM X

The uranium from which the uranium X was thus separated was left much less radioactive.   If this uranium was laid aside for a time, it was found to *regain its original radioactivity*.

The uranium X, on the other hand, *gradually became less active*, until after a few weeks its radioactivity was only half as intense as when it was first precipitated.

The rate at which uranium X loses its activity has been carefully studied.   Similarly, the rate at which the uranium, from which the uranium X has been separated, regains its activity, has been measured.

These results show that the uranium X loses its radioactivity *just as rapidly* as the uranium *regains* its activity. In a word, that in ordinary uranium we have *uranium X undergoing decay at just the same rate that it is being formed*, and the condition that exists is one of equilibrium between these two opposite processes.

The *rate* at which uranium *recovers* its radioactivity has been found to be *entirely independent of the conditions* to which it is subjected.

The *rate* at which uranium X *loses* its activity has also been found to be *entirely independent of all conditions both*

physical and chemical. It is unaffected by the state of aggregation of the radioactive matter, by the presence of any chemical reagent, and what is more surprising, by the temperature to which it is subjected.

We can now see why the radioactivity of uranium is constant. It represents, as mentioned above, a condition of equilibrium between the two oposite processes — the continual production of the radioactive uranium X at a *constant rate,* unaffected by any change of conditions; and the continual decay of the activity of the uranium X at a constant rate, also independent of all conditions. As both of these processes go on at a constant rate, the equilibrium between the two represents a condition where there is a constant amount of uranium X in the uranium, and hence a constant radioactivity.

RADIATION FROM URANIUM X

One other matter of importance and interest should be mentioned before leaving the discussion of radium X.

A peculiarity in connection with the radioactivity of uranium has already been pointed out. It does not give off an emanation.

The radiation from uranium X consists of β rays. These, as will be remembered, consist of negative charges of electricity shot off with a velocity nearly equal to that of light, and contain no matter whatsoever. In a word, they are cathode rays. The radiation from uranium X contains, then, no matter, but only electricity.

The recognition of this fact is of the very greatest importance in connection with the study of the relations between uranium and uranium X. The electrical method cannot be used in this connection, since the β rays produce but little ionization in a gas. The photographic method

must be employed. The neglect to take the above fact into account has led to some confusion in the literature of this subject.[1]

The facts just pointed out in connection with the radiations given off by uranium, on the one hand, and uranium X, on the other, are of prime importance in determining the radioactive products that are formed from uranium. In addition to uranium X, which gives off β particles, being formed from uranium, there must also be produced *another radioactive product* which sends off α particles.

As we have just seen, uranium X, or the active constituent which gives out β rays, has been separated from uranium; but the other active product which gives out the α radiations has not yet been separated by any means from salts of uranium.

CONTINUOUS FORMATION OF RADIOACTIVE MATTER FROM THORIUM

We have just seen that Sir William Crookes succeeded, by purely chemical means, in separating from uranium a radioactive constituent which was fundamentally different from uranium itself.

A similar separation has been effected by Rutherford and Soddy [2] in the case of thorium. When a thorium salt is dissolved in water and the solution treated with ammonia, the thorium is precipitated. When tested, the precipitate was found to be much less radioactive than the thorium salt. The solution from which the thorium had been precipitated by ammonia was, after filtering, completely evaporated, and the residue highly heated to remove salts of ammonia.

[1] Soddy: Journ., Chem. Soc., **81,** 860 (1902); Rutherford and Grier: Phil. Mag., **4,** 315, (1902).

[2] Journ. Chem. Soc., **81,** 837 (1902).

The final residue after heating was found to be very radioactive. Indeed, in some cases, more than a thousand times more radioactive than the thorium salt itself.

The highly active residue was very small in quantity, and, therefore, must have contained some substance whose radioactivity was very intense. This product obtained from thorium was called by Rutherford and Soddy *thorium X*, and assigned the symbol ThX.

This substance was shown to be soluble in water, since when thorium oxide is shaken with water the radioactive constituent is partly dissolved, while thorium oxide itself is insoluble in water.

If a solution of a thorium salt is treated with ammonium carbonate, the thorium X is precipitated along with the thorium. The method of separating thorium X from thorium is, then, very different from that required to separate uranium X from uranium. We shall now study some of the properties of thorium X.

PROPERTIES OF THORIUM X — DECAY OF ITS RADIOACTIVITY

Thorium X, when separated from thorium by the method above described, is highly radioactive as we have seen. Its radioactivity, however, decays, having only about half its initial value after four days.

The rate at which thorium X decays or loses its radioactivity, like uranium X, is uninfluenced by any known physical or chemical condition. Moisture, pressure, and even temperature have no influence on the rate at which thorium X decays.

THORIUM X PRODUCES THE THORIUM EMANATION

Both thorium and radium are capable of yielding that remarkable substance or substances already studied — the

emanation. In the case of thorium, does the emanation come from the thorium directly, or from thorium X? This has been answered by Rutherford and Soddy.[1]

If thorium X is completely removed from thorium by repeated precipitations, the thorium has no appreciable power to give off the emanation. If, however, the thorium is allowed to stand for some time, it can give off an appreciable quantity of the emanation. This is due, as we shall learn, to the production of thorium X which is going on in the thorium itself.

The thorium X when first separated from the thorium has marked power to produce the thorium emanation. As the thorium X decays it has been shown that its power to produce the emanation becomes less, and, indeed, in the same ratio. This shows that the thorium X produces the thorium emanation.

The changes that are going on in thorium can now be followed, at least in part. The thorium atom loses an α particle and produces thorium X. The thorium X, like thorium itself, is an unstable system and changes take place in it. The thorium X loses one or more α particles, and the thorium emanation is produced. The emanation is a different substance from thorium X from which it was formed. This conclusion is confirmed by a comparison of all of the properties of these two substances.

Thorium X differs from uranium X in the kind of radiation given out by it. Thorium X gives out chiefly α particles, while uranium X, as we have seen, gives out mainly β rays.

RECOVERY OF RADIOACTIVITY BY THORIUM

We have become familiar with a method for separating thorium X from thorium. This method effects almost

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[1] Journ. Chem. Soc., **81**, 849 (1902).

complete separation if the process is repeated a few times. If the thorium precipitated by ammonia is dissolved in nitric acid, and then again precipitated, and the process repeated twice, the resulting thoria is only about one one-hundredth as radioactive as ordinary thorium. The active thorium X has, thus, for the most part, been separated from the thorium.

If now this comparatively non-radioactive thorium is set aside, it regains its radioactivity. A careful study of the rate at which thorium recovers its radioactivity, after thorium X has been removed from it, has been made by Rutherford and Soddy.[1] They found that the thorium, in general, recovered its radioactivity *at the same rate* that the separated thorium X lost its radioactivity.

A careful comparison was made of the rate at which thorium X decays with time, and the rate at which thorium, from which thorium X has been separated, recovers its radioactivity, and the results plotted in curves. It was found that *the one loses its radioactivity just as rapidly as the other regains its radioactivity.*

This can best be interpreted by assuming that *thorium X is continually being produced by the thorium.* The rate of production is just equal to the rate at which thorium X decays, and this gives us the condition of equilibrium that obtains in ordinary thorium.

From the thorium which has regained its original radio-activity — and this requires about a month — a new portion of thorium X can be separated, and exactly the *same amount* as measured by its radioactivity that was obtained originally. The non-radioactive thorium, from which the second portion of thorium X had been separated, recovers its radioactivity again, at the same rate that it did initially. When

[1] Journ. Chem. Soc., **81**, 840 (1902).

the condition of equilibrium is reached again, a new portion of thorium X can be separated, which is equal to that originally obtained, and thus the process goes on slowly, apparently until all of the thorium is transformed into thorium X. This complete transformation would probably require millions of years.[1]

RATE AT WHICH THORIUM RECOVERS RADIOACTIVITY INDEPENDENT OF CONDITIONS

We would naturally ask whether transformations like those we have just been considering resemble ordinary chemical reactions, or are something fundamentally different from them? To throw any light on this question we must study the two sets of transformations, and see what resemblances or differences make their appearance. Chemical reactions are, in general, affected by the physical conditions of the substances that are reacting — by the state of aggregation, whether solid, liquid, gas, or solution; by the pressure to which they are subjected, and especially by the temperature.

The rate at which thorium X is formed from thorium seems to be *entirely independent of all these conditions.* It does not seem to matter to what conditions we subject the thorium from which thorium X has been separated, we cannot affect in any way the rate at which it recovers its lost radioactivity, which is the same as to say, the rate at which it produces thorium X.

There is, then, at least this one fundamental difference between the formation of thorium X from thorium, and ordinary chemical transformations — the former is independent of all the conditions to which the substances are subjected, including great changes in temperature.

[1] Journ. Chem. Soc., **81**, 844 (1902).

RADIUM DOES NOT GIVE RISE TO SUBSTANCES CORRESPONDING TO URANIUM X AND THORIUM X

Radium has not thus far been shown to yield any substance analogous to those formed by uranium and thorium, which we have just been studying. It does not form any intermediate product, but apparently *yields the emanation at once.*

We have, however, followed the transformations of radium through a number of stages, the more important of which, it will be recalled, are the following:

1. Radium gives off α particles and yields the emanation.

2. The emanation gives off α particles and yields emanation X, or Radium A.

3. Radium A gives off α particles and yields radium B.

4. Radium B gives off no radiation and yields radium C.

5. Radium C gives off α, β, and γ rays and yields radium D.

6. Radium D gives off no radiation and yields radium E.

7. Radium E gives off β and γ rays and yields, as we shall see in the last chapter, radium F, which also gives off α particles.

CHAPTER XVI

Theoretical Considerations

IMPORTANCE OF A THEORY OR GENERALIZATION

THE chief aim of scientific investigation is not the discovery of isolated facts. Indeed, we might continue to unearth such facts for an indefinite time, in any branch of natural science, and it is a question whether such knowledge ought to be dignified with the name of science.

The highest aim of scientific investigation is to reach a theory or generalization, which, when sufficiently established, becomes a *law*. This may or may not be an ultimate truth, probably is not, but may be as near to it as the methods at present at our disposal are capable of leading.

It may be asked, how do we arrive at generalizations in science? The answer is, for the most part by the inductive method. We discover fact after fact and then coördinate and correlate these individual facts, and the result is a generalization.

It may then be said, and fairly, that the discovery of facts is highly important, indeed essential to the discovery of generalization or law. From this no man of science will dissent. The discovery of isolated facts bears the same relation to science as the making of bricks to architecture. The bricks are absolutely essential in constructing the building, but *they are not the end or aim* of the architect. They are simply a means toward the end, which is utility, or beauty, or both. Just so in the investigation of natural

phenomena; we must study the isolated facts; they are the bricks or individual units of which science is made. They are, however, not science, and not the end of scientific investigation. They are but the means to the end. The generalization in science may be compared with the finished edifice in architecture.

We have now studied a large number of facts pertaining to radioactivity. Some of these are of a striking nature, and arouse deep interest when considered by themselves. Their real importance and significance, however, comes out when we consider them in *their relations to other facts*, and especially to well-established generalizations, which we now accept as the philosophy of the physical sciences.

We shall next attempt to coördinate the facts of radioactivity, and see what generalizations have been reached. We shall learn that new light has been thrown on the nature of what we call in chemistry the atom, and on the genesis of matter, by the study of various phenomena connected with radioactivity.

THE MORE IMPORTANT FACTS IN CONNECTION WITH URANIUM

Before taking up the generalizations that have been reached, a brief summary of the facts in connection with the several radioactive elements will be given, by way of review, since it is these facts that have to be dealt with primarily by any theories that have been, or may be, proposed.

The element uranium gives off α, β and γ rays. The *alpha rays* are composed of material particles, each having a mass from two to four times the mass of the hydrogen atom. These particles are shot off at very high velocities, and, therefore, have considerable kinetic energy. The α particles are charged, and are, therefore, deflected in a

magnetic field. The direction of their deflection shows that they are charged positively. Every α particle carries a unit electrical charge, as we say; that is, the amount of electricity carried by a univalent ion in solution.

The α particles produce strong ionization of the gas through which they pass; indeed, most of the ionization effected by radioactive substances is due to the α particles.

The α particles have marked power to produce phosphorescence in certain substances, especially zinc sulphide and barium platinocyanide. The phenomena that manifest themselves in the spinthariscope are due, for the most part, to the α particles.

The α rays produce but little effect upon a photographic plate, and, therefore, the photographic method cannot be used to measure the intensity of this kind of radiation. The α particles being material in nature are easily cut off by matter. They cannot pass even through very thin metallic screens.

The β rays are closely analogous to the cathode rays. The mass of the β particle is about $\frac{1}{770}$ of the mass of the hydrogen ion. These particles are shot off with different velocities, but all with very high speed, indeed, of the order of magnitude of light. The mass being small, the kinetic energy of the β particle is much less than that of the α particle, notwithstanding the fact that the β particle moves with greater velocity.

The β particles are deflected by a magnetic field, indeed much more strongly than the α particles. They are, however, deflected in the opposite direction to the α particles, and have a negative charge. Every β particle is a unit negative charge of electricity.

These particles produce comparatively little ionization in the gas through which they pass.

They have comparatively little power to excite phosphorescence. The β particles have greater effect upon a photographic plate than the α particles. They are cut off by metallic screens of any considerable thickness, but have much greater penetrating power than the α rays.

The *gamma rays* are analogous to the X-rays. These rays are apparently shot off *as pulses*, with very high velocities. The γ rays are not deflected at all even by a very intense magnetic field. They produce comparatively little ionization in gases, and have but little power to excite phosphorescence. Like the β rays, they have marked action on a photographic plate. They have great penetrating power; not only many times greater power to penetrate matter than the β rays, but even greater penetrating power than the X-rays themselves. As has already been pointed out, Rutherford has been able to detect the γ rays from radium after they have passed through a foot of solid steel. Gamma rays are probably produced by the β rays, and are never present without them.

Uranium is continually but very slowly undergoing a transformation, giving rise to a form of matter that differs in properties from the uranium itself. This new form of matter is called uranium X. The rate at which uranium X is formed is independent of all physical and chemical conditions. In the formation of uranium X from uranium, α particles are given off.

Uranium X, in turn, undergoes decomposition, giving off β and γ rays during the process. The rate of the decomposition is also independent of all conditions.

THE MORE IMPORTANT FACTS IN CONNECTION WITH THORIUM

The facts in connection with thorium are more numerous than with uranium. Thorium, like uranium, gives off α, β

and γ rays. It undergoes a continuous transformation, yielding a new form of radioactive matter known as thorium X, at the same time setting free α particles.

Thorium X gives off α and probably β particles, and yields an emanation — the thorium emanation — which is a gas. This emanation gives off α particles and forms emanation X, a radioactive solid which undergoes still further decomposition in at least two stages. In the first stage no rays are sent out, while in the second stage α, β and γ rays are emitted.

Since thorium gives rise to an emanation which decomposes into a solid form of matter — emanation X — that is radioactive and deposits upon other objects, thorium is capable of inducing or exciting radioactivity in bodies placed in its neighborhood. Thorium thus differs strikingly from uranium, which forms no emanation, and which, therefore, cannot induce radioactivity on neutral objects even when in close proximity to them.

THE MORE IMPORTANT FACTS IN CONNECTION WITH RADIUM

The best studied of all the strongly radioactive substances, by far, is radium. Its radioactivity is more than a million times that of metallic uranium, which is taken as the standard unit.

Radium does not yield any radioactive substance analogous to uranium X or thorium X. It appears to produce the emanation at once from itself, giving off α particles. The emanation gives off α particles, and emanation X or radium A results. This undergoes a number of transformations, no less than five having already been recognized. During the first transformation α rays are sent off; during the second no rays are emitted, while during the third stage of the transformation α, β and γ rays are all

given out. During the fourth stage of the transformation no radiations are given off; while during the fifth stage β and γ rays are liberated. Radium possesses a number of unique properties, all of which are very remarkable. Radium is the only known chemical element that produces of itself another chemical element, or can be made to produce such by any known means. Radium, or more exactly, the radium emanation, in undergoing decomposition spontaneously yields the element helium. This discovery was so surprising and so directly at variance with all of our previous conceptions of a chemical element, that it was subjected to the severest experimental tests. It has withstood all criticism, and is beyond doubt a fact.

A number of the other properties of radium are scarcely second in importance to the production by it of helium. Radium has the power of charging itself electrically, and it is the only substance known that has this power.

Radium also has the property of producing light or becoming self-luminous.

Most remarkable, however, is the amount of heat that is being continuously set free from radium. It will be remembered that radium produces enough heat to melt its own weight of ice every hour.

When we consider the almost limitless time over which radium can thus continue to give out heat, we see how enormous is the amount of energy that this substance can liberate. It is of a magnitude entirely incomparable with the amount of heat set free in the most strongly exothermic chemical reactions. The enormous magnitude of the energy that can be liberated by radium must be classed as one of the most important discoveries in modern science.

With the facts enumerated above at our command we can now proceed to discuss intelligently the generalizations

and conclusions that have been reached as the result of the study of radioactivity.

THEORY OF RUTHERFORD AND SODDY TO ACCOUNT FOR RADIOACTIVE PHENOMENA

The only theory thus far proposed, which accounts at all satisfactorily for the phenomena discovered in connection with the radioactive elements, and which will probably prove to be of epoch-making importance, is that advanced by Rutherford and Soddy.[1] The key to this theory is *that the radioactive elements are unstable.* The atoms of these substances represent *unstable systems,* which are continually undergoing rearrangement and decomposition. A definite number of the atoms of any radioactive element become unstable in any given time. They each throw off an α particle, and the next stage results. In the case of uranium and thorium, there are formed uranium X and thorium X. These products are in turn unstable. They throw off α particles, and in the case of thorium an emanation results. The radium atom throws off an α particle or α particles, and yields at once the emanation.

The emanation also is in an unstable condition. It throws off α particles and yields a radioactive solid, which, when deposited upon non-radioactive matter, induces in it radioactivity. This solid, or emanation X, or radium A as it is termed, is also unstable and undergoes further transformations. In the case of radium a fairly large number of steps have already been traced. In the earlier stages of the transformations of emanation X either α particles or no radiations escape. When no radiation is given out and we still have a well-marked transformation taking place, it probably means that the parts of the atom are

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[1] Phil. Mag., **5,** 576 (1903).

simply undergoing *rearrangement* without losing any constituent.

The β and γ rays are given off only in the *later stages* of the decompositions that are taking place in the radioactive atoms.

These unstable atoms, which are thus undergoing change, are termed by Rutherford *metabolons*.

THE TRANSFORMATIONS OF THE RADIOACTIVE ELEMENTS DIFFER FUNDAMENTALLY FROM ORDINARY CHEMICAL REACTIONS

The question that would at first arise is this: Are the changes that are going on in the radioactive elements fundamentally different from chemical reactions? New substances with different properties from the original substances are being formed. Energy in the form of heat is liberated, and these changes are characteristic of ordinary chemical transformations. If we study more closely the changes that are taking place in radioactive matter, we shall find marked differences between them and chemical reactions, as has already been pointed out.

In the first place, the changes in radioactive matter take place at a *definite rate, which is entirely unaffected by conditions.* We have studied a number of such radioactive changes which go on at the same rate at the temperature of liquid air as at a red-heat. This alone would show that the transformations in radioactive matter are fundamentally different from chemical reactions. The latter, as we well know, are greatly affected by conditions, and especially by temperature. The velocity of chemical reactions is in general greatly increased by rise in temperature, and at very low temperatures becomes extremely small or entirely vanishes.

Again, the *velocity with which radioactive changes take place is very small.* The amount of uranium transformed into uranium X, or thorium into thorium X, in considerable intervals of time, is very small indeed.

The *slowness* of the transformations that we have just been considering explains why such elements as thorium, uranium, and the like still exist, and have not all been transformed into their decomposition products. It is calculated that at least *thousands of years would be required for enough thorium to be transformed into thorium X, in order that the transformation would be detectable by the most sensitive balance.* Even radium yields the emanation very slowly. In fact, so slowly that the loss of a particles cannot even be weighed until larger amounts of radium are obtainable. It has been calculated that radium will transform half of itself in about 1,500 years. The loss, therefore, can scarcely be detected during the time over which measurements of radioactivity have thus far been extended.

That radium is, however, undergoing decomposition is certain, and if it were not being produced in some way all of the radium now in existence would eventually disappear. That radium is being continually produced, probably from uranium, will be shown in the next chapter.

Another marked difference between the transformations that are taking place in radioactive matter and chemical reactions is in the *amount of energy set free.* We have already become familiar with the fact that radium liberates quantities of energy incomparably greater than any other known substance. If we compare the amount of heat set free when the most vigorous chemical reactions take place, with that liberated by salts of radium, the former is utterly insignificant.

We must, therefore, abandon any attempt to explain

the transformations of the radioactive elements on the basis of chemical reactions. The two processes take place according to different laws. They are affected differently by change of conditions. They yield different products, considered both from the standpoint of matter and of energy. In a word, they are fundamentally different processes.

It is one thing to point out that radioactive processes are not chemical reactions; it is a different matter to find out the nature of the transformations that are taking place in radioactive substances. That we have a satisfactory suggestion to account for these transformations will now appear.

THE ELECTRON THEORY OF J. J. THOMSON AS APPLIED TO RADIOACTIVITY

It would be difficult to account for the instability of the chemical atom on the older theory that a chemical atom is a homogeneous, indivisible unit. In terms of the modern theory of the atom advanced by J. J. Thomson, we can readily see how an atom could be unstable and send off particles, just like the radioactive atoms do.

In terms of the theory of Thomson, which we have called the electron theory, a chemical atom, as we saw in earlier chapters, is made up of a large number of electrons or negative electrical charges, moving within a sphere of uniform, positive electrification. The particles are held in their relative positions by their mutual repulsions, and the attraction of the positive electricity. The heavier atoms contain a larger number of electrons than the lighter atoms — the approximate number in any atom being expressed by the atomic weight of that atom in terms of hydrogen as unity, multiplied by 770.

We can easily conceive of some of the electrons, in their rapid movement, coming into such a position that they

would escape and fly off from the atom into space. This would be especially the case with the *heavier atoms*, which represent very complex systems of electrons. From such highly complicated systems we might expect a more or less *constant* escape of such particles.

Again, we might not only expect individual electrons to escape from the atom, but *groups of electrons*. Indeed, groups of these negative electrical charges would be more likely to escape from the atom than single charges.

The facts of radioactivity are in perfect accord with the above conclusions. It is the atoms with largest mass that are radioactive. Thorium has an atomic weight of 232.5, uranium of 238.5 and radium either 225, or more probably in the neighborhood of 256 or 258. No radioactive substance is known having a small atomic weight, and all of the heaviest atoms are radioactive.

In the earlier stages of radioactive change it is the *a* particles that are shot off. The *a* particles have a mass probably about twice that of the hydrogen atom. This means that they are groups of about twice 770 electrons, that are shot off from the radioactive atom. The atom, having lost this comparatively large number of electrons, is different in nature from the original atom. The system is not yet stable, and another *a* particle or complex group of electrons is shot off, and another condition of the radioactive matter produced. This may continue through several stages, until after a while the *individual* electrons begin to come off as the *β* particles. It will be remembered that the *γ* rays are set up where the *β* rays impinge upon solid matter.

Thus we see that the theory of matter advanced by J. J. Thomson, and which was developed at some length in the earlier chapters, enables us to account rationally for many

of those remarkable phenomena that we have studied under the general head of radioactivity. Further, it is the only theory that has thus far been proposed, which enables us to deal at all satisfactorily with the unstable atom.

IS MATTER IN GENERAL UNDERGOING TRANSFORMATION?

The raising of such a question would, until a few years ago, have been regarded as extraordinary, since the elements were regarded as stable and unchanging. In the light of the recent investigations with the radioactive elements, it is most pertinent. There is some evidence, as we shall see, that all the elements are radioactive to a very slight extent. If this should be proved to be due to the elements themselves, to be a property inherent in all matter, and not caused by the deposition of some form of radioactive matter, then, from what has been said above, we must regard matter in general as undergoing change. This change is slow, very slow, but is progressing continuously; the more complex, unstable forms, breaking down into simpler aggregates of electrons.

If it should be shown that all matter is slightly radioactive, as seems not improbable, then we should be forced to the conclusion of the general instability of the chemical elements. However this may prove to be, enough has already been established to show that our former conceptions of the nature of the chemical element must be fundamentally modified.

CHAPTER XVII

WIDE DISTRIBUTION OF RADIOACTIVE MATTER AND THE ORIGIN OF RADIUM

THE most strongly radioactive substances — radium, actinium, polonium — apparently occur in very small quantities. Even the more feebly radioactive elements, thorium and uranium, are not among the more common chemical elements.

A question of very great importance in connection with the study of radioactivity is this: Is radioactive matter small in quantity and confined to a few sets of conditions, or is it widely distributed? The fact that it exists in any one locality, or in any one mineral only in small quantity, does not throw much light on the question of the scope of its distribution.

We shall review very briefly some of our knowledge of the distribution of radioactive matter, as far as our globe is concerned.

RADIOACTIVE MATTER IN THE EARTH

It has been shown by Elster and Geitel [1] that air confined in spaces in contact with the earth, such as certain caves, becomes radioactive. The same result was obtained, and to a more marked extent, by taking air from some depth below the surface of the soil by means of a pump. Such air contained sufficient quantity of the radium emanation to induce radioactivity upon the walls of the containing

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[1] Phys. Zeit., **3,** 574 (1902).

vessel, especially if it was charged negatively. The radio-activity decayed at such a rate as to leave no question that it was produced by the radium emanation. These phenomena were shown to be due to the presence of radium in the ground, which diffused into the air; since air confined by itself in a metal vessel, away from contact with the soil, did not become radioactive.

Similar results have been obtained by others, so that there is now no reasonable doubt that the radioactivity of air in confined spaces is due to the presence of the radium emanation, which gradually diffuses from the ground.

It was shown by Ebert that air which is radioactive, loses its radioactivity when passed through a tube surrounded by liquid air. It will be remembered that Rutherford, by this means, condensed the emanation from radium, and obtained it in the liquid condition. This is another bit of evidence that goes to show that the radioactivity of the air in contact with the earth is due to the radium emanation.

The amount of radioactive matter in the soil seems to vary greatly from place to place. Clay soil seems to be the most radioactive, but sandy soils are not infrequently radioactive.

Carbon dioxide that came from great depths in the earth was found to be radioactive. It lost its radioactivity on standing for some days.

A quite appreciable quantity of radioactive matter has been found in certain waters that percolate through the soil, and especially in those that come from considerable depths. J. J. Thomson [1] has shown that the tap-water of Cambridge, England, contains radioactive matter, while the waters from certain deep wells in other parts of Eng-

[1] Phil. Mag., **4,** 356 (1902).

land were found to contain quite appreciable quantities of the highly radioactive emanation. This emanation decayed at such a rate, as compared with the emanation from radium, as to show that the two were identical.

Similar results were obtained by Bumstead and Wheeler[1] with the waters at New Haven.

One of the most interesting results of this character has been found in connection with certain hot springs, such as at Bath, in England. The water of this spring, which comes from great depths, is slightly radioactive, but the mud deposited from the water is strongly radioactive, due to the presence of the radium emanation.

It is also a matter of importance that in the gases that escape from this spring, *helium has been found*. This helium comes, almost beyond question, from the decomposing radium emanation, and shows that radium exists at great depths beneath the surface of the earth.

The simultaneous occurrence of these two elements, and the fact that helium is produced from the radium emanation, lead us to suspect the presence of radium wherever helium is found — as in the sun.

RADIOACTIVE MATTER IN THE AIR

It has been known for some time that a charged body surrounded by air may lose its charge rather more rapidly than can be accounted for by the leak through the supports. This would indicate that the air is ionized to some extent.

The cause of this ionization remained for a long time unknown, and, indeed, has only recently been discovered. After the discovery of radium and its comparatively wide distribution, it occurred to Elster and Geitel that radium

[1] Amer. Journ. Sci., **17**, 97 (1904).

might be present in small quantity in the air, and if so, this would account for the ionization and conductivity of the air. They undertook to test the atmospheric air for the presence of radioactive matter, and in the following manner.

It had already been shown by Rutherford that a negatively charged wire, suspended in the presence of the emanation from radium or thorium, would collect upon it the radioactive decomposition products of the emanation. Elster and Geitel,[1] utilizing this fact, exposed a long wire charged to a high negative potential to the air, and then tested it for the presence of radioactive matter.

After the wire had been thus exposed for several hours, it was placed in a closed vessel with a charged electroscope. The latter was discharged much more rapidly than normally, showing the presence of radioactive matter upon the wire, which ionized the gas around the electroscope.

The presence of radioactive matter upon the wire was further shown by rubbing the wire with a piece of drying paper that had been dipped in hydrochloric acid. The paper became quite strongly radioactive. When a long, negatively charged wire was suspended in air that had remained undisturbed for some time in contact with the earth, as in certain caves; Geitel[2] showed that enough radioactive matter was deposited upon the wire, which, when removed by a piece of leather moistened with ammonia, produced a visible phosphorescence in barium platino-cyanide when the salt was brought near to it. This radioactive matter also exerted an action on a photographic plate, and photographs were obtained by Geitel by means of it.

[1] Phys. Zeit., 2, 590 (1901).
[2] Phys. Zeit., 3, 76 (1901).

The same experimenter studied the rate at which the radioactive matter upon the negatively charged wire underwent decay. It was found to decay like the radioactive matter deposited from the radium emanation.

If the wire was charged positively no radioactive matter was deposited upon it. Since the radioactive matter was drawn to, and deposited upon a negatively charged wire, and not upon a positive wire, we must conclude that the radioactive matter in the air is charged positively.

All of these facts point to one conclusion. The radioactive matter in the air comes from the radium emanation. This shows that *radium emanation is present in the atmosphere.*

The amount of radium emanation in the air varies greatly in different localities. In certain cases the radioactivity of the air is relatively great, as has already been stated. The amount of radium emanation in the air in some localities is more than a dozen times as great as in other regions. Certain experiments made in northern Norway would seem to show an abnormally great amount of radium emanation in the air in that region.

Since the radium emanation in the air probably comes from radium in the soil, the amount of the emanation in the air in any large locality may be taken as a rough index of the amount of radium in the soil in that locality. This is, of course, only an approximate relation, unless frequently repeated tests were made, since the winds shift the air so frequently from one region to another.

Elster and Geitel [1] found that the radioactivity of the air not only changed from one locality to another, but was not constant in any given locality. It varied with a number of conditions. On cold, frosty mornings the activity was unusually high. The lower the barometer the greater the

[1] Phys. Zeit., **4**, 522 (1903).

induced radioactivity in the air in any given region. This is just what would be expected if the radioactive matter in the air came from radium in the earth. The radium emanation, being a gas, diffuses from the earth in which it is formed from the radium present there, into the atmosphere. The lower the barometric pressure the more emanation will pass out of the fissures and fine pores in the earth into the atmosphere. Since the radioactive matter in the air comes from the radium emanation, the lower the barometer the more radioactive matter present in the air.

All of these facts point to the same conclusion, which is that already stated, that the air contains a form of radioactive matter. This conclusion is still further confirmed by the following facts:

If the air contains radioactive matter, we might expect that some of it would be carried along with objects moving through it.

Fortunately the means for testing this conclusion are supplied to us by nature. When *drops of rain or flakes of snow fall through the atmosphere they might be expected to carry down with them some of the radioactive matter in the air.* This has been tested by C. T. R. Wilson [1] in England, and in the case of snow by Allan [2] in Canada. Wilson found that freshly fallen rain showed the presence of quite an appreciable amount of radioactive matter. This radioactivity, however, rapidly decayed.

If barium chloride is added to freshly fallen rain, and the barium precipitated by sulphuric acid, the barium sulphate that is thrown down is quite radioactive, showing that the radioactive matter in the water is carried down with the precipitate.

[1] Cam. Phil. Soc. Proc., 11, 428; 12, 17 and 85 (1902–1903).
[2] Phys. Rev., 16, 237, 306 (1903).

Both Wilson and Allan found that newly fallen snow was radioactive. When a considerable quantity of the snow was melted and the resulting water evaporated, a radioactive residue was left behind.

The radioactivity, however, rapidly decayed, as in the case with the freshly fallen rain. All of the above facts taken together leave no reasonable doubt as to the presence of radioactive matter in the air.

IS MATTER IN GENERAL RADIOACTIVE?

Having found a number of chemical elements that are radioactive, and having shown that these are radioactive to such different degrees, the question naturally arises, Are there not other substances that possess radioactivity? It is possible that there may be a large number of the chemical elements that are feebly radioactive, or all matter might be radioactive to some slight extent, as has already been mentioned.

The first experiments bearing upon the broad question were those of Mme. Curie, and these gave negative results. She examined a large number of the chemical elements for radioactivity, and found it manifested only by those already considered. The question in this connection is whether the method employed by Mme. Curie was sufficiently sensitive.

An exactly opposite result has since been obtained by a number of investigators, and especially by Strutt.[1] It seems now to be fairly well established that ordinary matter, in general, is radioactive to a very slight extent, but unquestionably radioactive.

Having settled this point, it still remains to determine whether this slight radioactivity is due to the substances

[1] Phil. Mag., 5, 680 (1903).

themselves, or to radioactive matter deposited in minute quantities upon them. There are, as yet, not sufficient data to enable us to answer this question finally.

THE ORIGIN OF RADIUM

We have seen that radium is unstable, undergoing continual decomposition. From the rate at which radium is decomposing, it has been pointed out by Rutherford that if the whole earth were pure radium, a few thousand years hence it would have only the radioactivity of pitchblende.

Since many of the minerals that contain radium have existed much longer than the above period, it is obvious that radium must be produced from something, or all of the radium would long since have disappeared. The interesting and important problem is, then, to find out what is the source of radium; from what substance or substances it is produced.

Since radium occurs in uranium minerals, it was early suspected by Rutherford that radium might be produced from uranium.

Soddy, working with Rutherford, took up this problem and published his results in 1904.[1] A kilogram of uranium nitrate was freed from radium until it contained less than 10^{-13} grams, which was the smallest quantity that could be detected by the electroscope. The uranium nitrate was then allowed to stand for twelve months, and was tested again for radium. Soddy points out that the presence of radium in the laboratory renders the electroscopes incapable of detecting such minute traces of radium as they otherwise could do. He, however, feels justified in stating that the amount of radium in the kilogram of uranium nitrate, after it had stood for a year, was less than 10^{-11}

[1] Nat., **70**, 30 (1904).

grams. Soddy concludes that this settles the question as far as the production of radium from uranium is concerned. Uranium cannot be regarded as the parent of radium, since from the above result, if any radium is produced from uranium, less than one ten-thousandth of the theoretical quantity necessary to maintain the present condition of equilibrium is produced.

Soddy recognizes that if substances intermediate between uranium and radium were formed, his result could be explained. He, however, thinks that such assumptions are not justified.

Just a week prior to the publication of the paper by Soddy in *Nature*, a short article appeared in the same journal by Whetham,[1] in which he stated that he had examined several specimens of uranium compounds, which had been preserved in the laboratory from seventeen to twenty-five years. A larger amount of radium emanation was obtained from these old specimens, than from more recently prepared samples of these same uranium compounds.

This observation was, to say the least, suggestive, and made it highly desirable that more work should be done along this same line.

About this time a suggestion was made by Joly,[2] which is well worthy of serious consideration. Joly suggested that instead of radium being a disintegration product of uranium or thorium, it may be produced by the interaction of some of the radioactive substances with the non-radioactive constituents of pitchblende. Radium would then be a product of synthesis from simpler things.

This suggestion of Joly is especially important if it should

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[1] Nat., **70,** 5 (1904).
[2] Nat., **70,** 80 (1904).

be shown that the atomic weight of radium is greater than that of thorium or uranium. We should naturally expect these substances, in breaking down, to yield products with smaller atomic weights than their own. If radium has a larger atomic weight than either of these radioactive elements, it is a little difficult to see just how it could be formed as the direct result of their disintegration. It might, however, be produced by the recombination of certain of the decomposition products of these elements with one another, or, as Joly suggests, by the combination of these with other substances occurring in the pitchblende.

Some light has been thrown by McCoy [1] on the possible origin of radium. He pointed out that if radium is a decomposition product of uranium, all uranium minerals must contain radium, and in quantities proportional to the amounts of uranium in the minerals. Since all intermediate products, such as uranium X, the radium emanation, etc., are present in these minerals in quantities proportional to the total amounts of uranium, it follows that the total radioactivity of every natural uranium ore is proportional to the amount of uranium contained in it.

McCoy analyzed a number of uranium ores from different localities, and determined their radioactivities by means of the electrical method. He found that the activity of all uranium ores, which did not contain appreciable quantities of thorium, was directly proportional to the amount of uranium contained in them. In other words, the radioactivity of any given quantity of uranium ore, divided by the percentage of uranium contained in it, is a constant. This constant was termed the activity coefficient.

It was further shown that the radioactivity of chemi-

[1] Ber. d. deutsch. chem. Gesell., **37,** 2641 (1904).

cally prepared uranium compounds is directly proportional
to the amount of uranium contained in them.   Such com-
pounds also have a constant activity coefficient.

More elaborate experiments on this same problem have
been made by Boltwood,[1] who arrived, however, at essen-
tially the same result. The amount of radium contained
in the uranium minerals was determined by measuring
electrically the emanation that is given off when a weighed
quantity of the mineral is dissolved or decomposed, and the
solution boiled or allowed to stand in connection with a
closed glass vessel. We can measure the activity of the
emanation very accurately, and this furnishes us with a
reliable means of measuring the amount of radium in a
given substance if there are no other emanating substances
present.   If we simply wish to determine the relative amounts
of radium in any two substances, it is only necessary to meas-
ure the activity of the emanation produced by equal weights
of these substances.

Boltwood used an improved method for analyzing the
uranium minerals, which is obviously very important.
The results that he obtained for somewhat more than
twenty uranium minerals are quite satisfactory, pointing
conclusively to the proportionality between the amount of
radium in the mineral and the amount of uranium present.

To give a more exact idea as to the meaning of this rela-
tion, Boltwood divided the amount of radium in the mineral
by the amount of uranium, to see whether the ratio would
be constant for the different minerals. The author con-
cludes that from his results there is direct proportionality
between the quantity of uranium and the quantity of radium
in the minerals, and that *radium is formed from uranium.*

[1] Amer. Journ. Sci., **18,** 97 (1904); Phil. Mag., **9,** 599 (1905); Nat., **70,**
80 (1904).

He points out that certain of the methods that have been used for determining uranium quantitatively are defective, which is obviously a matter of the greatest importance in the present connection.

Experiments similar to those of Soddy were carried out by Boltwood, to see whether radium is produced *directly* from uranium. He comes to the same conclusion as Soddy — that it is not. He agrees with the suggestion of Rutherford, that probably one or more intermediate products exist between the uranium atom and the radium atom. Such products, however, have not yet been discovered, unless the suggestion of Rutherford, that possibly actinium is such a product, is correct.

In a quite recent paper, Rutherford and Boltwood[1] point out that as the amount of radium in uranium minerals is proportional to the amount of uranium present in those minerals, the amount of radium to the gram of uranium in the mineral should, of course, be a constant. The value of this constant can easily be calculated, if the relative radioactivity of pure uranium and pure radium is known. To determine the amount of radium occurring in the mineral with say one gram of uranium, they compared the radioactivity of the emanation from the standard amount of pure radium bromide, with that from the mineral containing a known quantity of uranium.

They found that the amount of radium to one gram of uranium in uranium minerals is about 7.4×10^{-7} grams. One part of radium, therefore, occurs with about 1,350,000 parts of uranium.

From these data it is easy to calculate the amount of radium occurring in uranium ores. They find that in a ton of pitchblende containing sixty per cent. of uranium,

[1] Amer. Journ. Sci., **20,** 55 (1905).

which is a rich uranium ore, there is about 0.4 gram of radium. Lower grades of pitchblende, which contain less uranium, will contain proportionally less radium.

Boltwood also took up the earlier work of Soddy, in which the latter came to the conclusion that radium is not formed from uranium, because uranium nitrate which had stood for a year or so did not contain any appreciable quantity of radium.

He [1] repeated the experiment of Soddy and obtained similar results. A comparatively large quantity of uranium nitrate was carefully purified by recrystallization. One hundred grams were dissolved in water and the solution sealed up in a bulb. After standing thirty days the bulb was opened and all gases removed from the solution by boiling. All the gases removed from the solution were brought in contact with an electroscope. It was found that the amount of radium present in the uranium at the start was less than 1.7×10^{-11} grams. The uranium solution was again sealed up in the bulb and allowed to remain for six months. The amount of radium present was again tested and found to be less than 5.7×10^{-11} grams.

After 390 days the test was repeated, and with the same result; the amount of radium present in the solution still being less than 1.7×10^{-11} grams. If any radium was formed from the uranium during this period, the above results show that *less than one sixteen-hundredth* of the quantity required by theory was produced.

These results would seem to show pretty conclusively that *radium is not formed directly from uranium.* The work of McCoy and Boltwood, however, establishes a proportionality between the amount of radium in uranium ores, and the amount of uranium contained in them. Taking

[1] Amer. Journ. Sci., **20**, 239 (1905).

all these facts into account, we must conclude that *uranium is the parent of radium, but that the latter is not formed directly from the former.* One or more intermediate products with a slow rate of change must be formed. These on breaking down yield radium directly or indirectly.

It will be remembered that Rutherford suggested that actinium may be such a product. Whether this is the case, and what is the nature of such intermediate products, can be determined, if at all, only after a much larger amount of work has been done on this problem.

CHAPTER XVIII

Most Recent Work on Radioactivity

SOME PROPERTIES OF THE ALPHA AND BETA RAYS FROM RADIUM

RUTHERFORD [1] has undertaken a new determination of the velocity of the α particle, and of the ratio $\dfrac{e}{m}$ for this particle. His method is based upon the well-known principle of measuring the electrical and the magnetic deflections. The magnetic deviation had already been determined with a fair degree of accuracy, but it still remains to measure the electrical deviation more accurately. The difficulty is in obtaining a sufficiently large electrical deflection of the rays.

Some interesting facts have, however, already been brought out as the result of this work. It has been recognized that the α rays from radium are complex, consisting of particles projected at different velocities. It will be recalled that a number of the different products formed from radium give off α particles. Indeed, at least five such products exist in radium. The α rays from radium C pass through about twice the thickness of air that the α rays from radium itself do. Thus, each product from radium seems to give off α particles at a certain definite velocity. To measure the velocity of the α particles, those emitted by only one product must be studied at a time.

[1] Phil. Mag., **10**, 163 (1905).

The rays given off by the deposit from the emanation, which were really the α particles from radium C, were studied. When the experiments on the electrical deflection of the α particles are completed, Rutherford points out that the ratio $\frac{e}{m}$ will probably be ascertained with sufficient accuracy to enable us to decide whether or not the α particle is simply a rapidly moving helium ion.

An interesting result in connection with the heating effect of radium is referred to in this recent work by Rutherford. It will be recalled that about seventy per cent. of the heat liberated by radium comes from the emanation. It is shown that about *thirty per cent. of the total heating effect of radium comes from radium C, one of the decomposition products of the emanation.*

When the α particles pass through matter their velocity is diminished. When their velocity falls below a certain value they lose their properties of producing luminescence, of affecting a photographic plate and of ionizing gases. The interesting point is that *this value is the same in all three cases.* This would indicate, as Rutherford points out, that the three properties above mentioned have a common origin.

The absorption of the α rays by gases is due to the energy being used up in producing ions in the gas. Rutherford thinks that the phosphorescent action and the action on a photographic plate are primarily the action of ions. These would cease at about the same velocity that would just be necessary to ionize a gas.

The bearing of these results on the action of the spinthariscope is pointed out. Becquerel explains the action, as will be recalled, as due to a cleavage of the crystals of the phosphorescent substance. The action is probably to

be ascribed to the production of ions in the substance. When these ions recombine scintillations result.

We cannot ascribe the action of this instrument simply to the bombardment of the phosphorescent screen by the α particles, since we have just seen that these particles produce no scintillations or luminescence after their velocity has fallen below a certain definite value, and they still have, of course, considerable kinetic energy.

Rutherford raises the question as to whether phosphorescent and photographic effects in general may not be due primarily to the production of ions.

Since the α particles are shot off from radioactive matter with velocities that are only about thirty per cent. above the critical velocity, *i.e.*, the velocity necessary to affect a photographic plate, to produce phosphorescence, or to ionize a gas, and thus lead to the detection of the α particles, it suggests the possibility that *matter in general may be undergoing a disintegration similar to the radioactive elements*, but that the α particles are shot off with a velocity below the critical and therefore escape detection.

It is probable that in some of the transformations of the radioactive elements which are thought to be rayless, α particles are actually given off, but with a velocity that is below the critical and they therefore are not detected.

This suggests the further thought that *all matter may really be radioactive.* Only those elements that shoot off α particles with velocities above the critical would produce appreciable ionization in a gas, and thus be classed as radioactive, in terms of our present methods of detecting radioactivity.

The presence of an electrical charge upon the α particles has been demonstrated directly by J. J. Thomson.[1]   He

[1] Cam. Phil. Soc. Proc. (1904).

used radio-tellurium, which gives off only α rays. Some of this substance was placed at a distance of three centimetres from a metal plate which was connected with a gold-leaf electroscope. When a vacuum was established the electroscope leaked véry rapidly if positively charged, but only very slowly if negatively charged. When the apparatus was placed in a strong magnetic field the positive leak was slight, due to the electrons being bent away by the field.

The experiment was then tried of placing the radio-tellurium closer to the metal plate in a strong magnetic field. Under these conditions the electroscope became charged positively, showing that the α particles were charged positively. Recent experiments by Rutherford led to exactly the same result. Rutherford[1] also determined the *total number of particles shot off by radium.* In order to get rid of the β particles from radium he removed the emanation and all of its successive decomposition products, and obtained radium at what is known as its minimum activity. Under these conditions the number of α particles shot off from a gram of radium per second is 6.2×10^{10}. The number of α particles shot off by normal radium in radioactive equilibrium is four, and possibly five times the number of β particles shot off under the same conditions; since radium, the emanation, radium A, radium C, and radium F all emit α particles, while only radium C and possibly radium E emit β particles. Radium, however, at its minimum activity is freed from the emanation and all succeeding decomposition products, and gives off the same number of α particles as normal radium gives off β particles. This also was tested by Rutherford. He found that the number of β particles shot off per second from one gram of radium was 7.3×10^{10}. This is almost identical with the result

[1] Phil. Mag., **10**, 193 (1905).

obtained for the number of α particles at minimum activity.

This result is a striking confirmation of the theory which predicted it.

The importance of the above determinations is obvious. Knowing the number of α particles shot off from radium in a given time, we can calculate approximately *how rapidly radium decomposes*. It is probable that one α particle is expelled from a radium atom when the atom breaks down. This would show that in a gram of radium 6.2×10^{10} atoms of radium break down every second. Since one gram of radium contains approximately 3.6×10^{21} atoms, the life of radium, as Rutherford shows, is about 1850 years.

He also points out that knowing the number of α particles shot off from radium, we can calculate the *volume of the emanation produced by it*. Every atom of radium in breaking up gives off at least one α particle and produces one atom of the emanation which is a gas. A cubic centimetre of a gas is known to contain about 3.6×10^{19} molecules. From these data the volume of the emanation that can be obtained from a gram of radium is calculated to be 0.83 cubic millimetre. The volume of the emanation from a gram of radium, as found experimentally by Ramsay and Soddy, was one cubic millimetre. The two results, when we consider the conditions, are strikingly concordant.

Rutherford [1] also points out that from the number of α particles expelled from radium we can *calculate the heating effect*, since this is due to the bombardment of the α particles. He calculated the kinetic energy of the α particle to be 5.9×10^{-6} ergs. Radium at its minimum activity gives off, as we have seen, 6.2×10^{10} α particles from a gram per second. In radioactive equilibrium it gives off $4 \times 6.2 \times 10^{10} = 2.5 \times 10^{11}$

[1] Phil. Mag., **10**, 206 (1905).

α particles per gram-second. This would correspond for a gram of radium to 126 gram-calories per hour. The value found was 100, which agrees well with the above calculation.

Some interesting and important investigations on the α particles sent off by radium have very recently been made. Certain results obtained by Bragg and Kleeman [1] have thrown new light on the nature of these particles as sent off by radium in its various stages of decomposition. They determined the ionizing power of the α particles, and from the nature of the results obtained, seem justified in concluding that the α *particles given off by radium in any one stage of its decomposition are of the same nature.*

When radium is in radioactive equilibrium, we have α particles given off with very different velocities. This is due to the fact that the several products of the decomposition of radium are all present. It is an important and interesting fact to know that while the α particles given off by the different stages through which the radium passes, have different velocities, the particles given off by radium in any one of its stages of decomposition all have the same velocity and the same ionizing power.

The following interesting, although empirical relations, have apparently been established by Bragg and Kleeman. The so-called "stopping power" of a number of the elements for the α particle was determined, with the result that the *amount of energy spent by the α particle in producing ionization in an atom seems to be proportional to the square root of the atomic weight of the substance ionized.* Quite a number of elements have been brought within the scope of the investigation, with the result that the above relation seems to hold approximately.

[1] Phil. Mag., **10**, 318 (1905).

They have also shown that the number of ions produced by an *a* particle is the same, no matter what the nature of the gas through which it passes, and, further, that the *same amount of energy* is always required to make a pair of ions, regardless of the nature of the atom or molecule from which they are made.

This latter relation is probably very important, since it shows that ionization is essentially the same process, regardless of the nature of the molecules of the gas in which it takes place.

The deflection of the *a* particles in a magnetic and in an electrostatic field, has recently been determined by Mackenzie,[1] working in the laboratory of J. J. Thomson. By this means the velocity of the particles could be determined, and also the ratio of the charge *e* to the mass *m*. In this work, radium which was in radioactive equilibrium was employed. Under these conditions radium is sending out *a* particles with very different velocities, and what is really determined is the mean velocity.

In the magnetic deflection of the rays the *a* particles from the radium entered a brass vacuum-box by passing through a thin sheet of mica. The rays passed through a vacuum for about fifteen centimetres, and then fell on a screen of zinc sulphide. The line of scintillations was then photographed.

The poles of an electromagnet could be placed along the path of the rays, and when the magnetic field was applied the usual deflection of the *a* particles took place. This was registered photographically.

The mean value found for $\dfrac{mv}{e}$ was 3.00×10^5, varying between the extremes 2.5×10^5 and 3.7×10^5.

[1] Phil. Mag., **10,** 538 (1905).

The value of $\frac{mv}{e}$ found by Rutherford for radium in radioactive equilibrium is 3.9×10^5. The Mackenzie value must be corrected for the decrease in the velocity of the particles produced by passing through the thin sheet of mica. The corrected values are as follows: The average value of $\frac{mv}{e}$ for the α particles as they leave the surface of the radium is 3.18×10^5; the extreme values being 2.65×10^5 and 3.92×10^5.

In measuring the electrostatic deflection an apparatus was employed which was similar in many respects to that used in measuring the magnetic deflection. The α rays entered the apparatus by passing through the mica plate, but they were now passed between two plates charged to a difference of potential as great as 10,000 volts.

The value found for $\frac{mv^2}{e} = 4.11 \times 10^{14}$.

The value of $\frac{mv}{e} = 3.00 \times 10^5$.

The average value of $v = 1.37 \times 10^9$ centimetres per second, and $\frac{e}{m} = 4.6 \times 10^3$ electromagnetic units.

The value of $\frac{e}{m}$ for the hydrogen ion is 10^4. If we assume that the α particle carries the same charge as the hydrogen ion, the value of m, or the *mass of the alpha particle, is about 2.2 times that of the hydrogen ion.* This is very close to the mass of the hydrogen molecule.

This work, then, does not favor the view that the α particles are helium ions, their mass being only about half that of the helium ion. Mackenzie points out that both hydrogen and helium may be given off simultaneously from radium, but this is certainly far from proved.

We must therefore still be cautious in drawing the conclusion that the α particles are nothing but helium ions.

The magnetic deflection of the α particles from polonium was also measured, and these were found to have somewhat greater velocity than the average α particles from radium.

Their velocity, however, was not as great as the swiftest α particles from radium.

SLOW TRANSFORMATION PRODUCTS OF RADIUM — RADIUM F

It will be recalled that Rutherford had already shown that radium passes through a number of transformations and gives rise to a number of substances.   These are: The radium emanation, radium A, radium B, radium C, radium D, and radium E.   Every one of these substances is the offspring of the preceding and the parent of the succeeding one.

In a very recent paper Rutherford [1] describes still another transformation product of radium, which he naturally calls radium F.   This is produced from radium E, which probably gives off β and γ rays.

For the method of demonstrating the existence of these various transformation products of radium, reference must be had to an earlier chapter where they were discussed at some length.

Radium F is deposited on a plate of bismuth in a solution of the active deposit.   It gives off only α particles, and its activity decreases to half-value in about 143 days.

An interesting *relation between radio-tellurium and radium F* is pointed out by Rutherford.   There are strong reasons for believing that the two are identical.   Radio-tellurium gives off only α particles and its activity falls to half-value in about 143 days.   Both are deposited on bismuth and

[1] Phil. Mag., **10,** 290 (1905).

the α rays from radio-tellurium are identical with those from radium F. Further, both give off only α rays.

The active constituent in radio-tellurium is, then, a product of the radium occurring with the tellurium in the minerals.

Radium F is much more active than pure radium. It has been shown by Rutherford to be about 3,200 times as radioactive as radium at its minimum activity, or 800 times as radioactive as normal radium.

This also corresponds with the enormous activity possessed by radio-tellurium, as demonstrated by Marckwald.

Rutherford thinks that polonium is probably a mixture of radium D and radium F, and that the chief constituent in radio-lead is radium D. He was led to this conclusion by studying the radiations from the several substances and the changes in these radiations with time.

The transformation products of radium with the radiations given out by each are, then, the following:

$$\alpha \qquad\qquad \alpha \qquad\qquad \alpha \qquad\qquad\qquad\qquad \alpha, \beta, \gamma$$
radium — emanation — radium A — radium B — radium C
$$\beta, \gamma \qquad\qquad \alpha$$
— radium D — radium E — radium F.
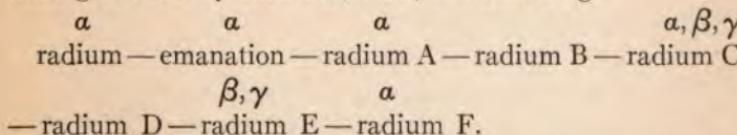
We have already seen that radium is almost certainly derived from uranium, but indirectly, there being one or more intermediate products that have thus far not been discovered. The relations are:

Uranium — uranium X, — — — radium — and then the above-named decomposition products of radium.

In the light of the above considerations we must still ask the question, what becomes of radium F? Does it undergo still further transformation, and, if so, into what?

Rutherford has thrown light indirectly on this question. We have no evidence that radium F passes into anything

that is radioactive. Radium apparently yields four sub-
stances that send off a particles — radium itself, the emana-
tion, radium A, radium C, and radium F. It has been
regarded as highly probable that the a particle is a charged
helium atom. It would then have a mass of four, and five
such particles a mass of 20. If the atomic weight of radium
is 225, the end product formed from radium F would have
an atomic mass of 205. The atomic weight of lead is 206.7.
Lead occurs in radioactive minerals in quantities propor-
tional to the uranium and to the radium. This argues in
favor of the conclusion that lead is the final product of the
disintegration of radium.

It will be recognized that the first argument is not at all
conclusive, since it involves several assumptions. In the
first place it is far from proved that the atomic weight of
radium is 225.

Again, it has not yet been proved that the a particle is a
helium ion. In the light of the most recent work this, as
we have seen, is doubtful.

The second line of argument based upon the presence
of lead in all uranium minerals and, therefore, in all min-
erals that contain radium, is far more convincing. Recent
analyses of uranium minerals confirm the relation pointed
out by Rutherford.

Other elements, such as hydrogen, argon, barium, bis-
muth, and thorium, occur frequently in radioactive minerals,
and it may be shown that some of these, in addition to
helium, are produced by the disintegration of radium. Up
to the present, however, the evidence in the case of lead
is the most satisfactory, but it cannot yet be regarded as
proved that lead is a decomposition product of radium.
Indeed, it seems to be very far from proved.

"RADIOBES" DESCRIBED BY BURKE

In discussing the work of Burke,[1] let us see first why he undertook the experiments about which so much has been written and said, and then see what are some of the results obtained. He was studying phosphorescence, and wanted to see whether it could not be produced in certain organic bodies by exciting agents.

He introduced some crystals of radium bromide into glycerol, and then plunged the whole into liquid air. He thought that these conditions were favorable to the condensation of the molecules around the ions from the radium.

Crystals of glycerol were obtained. It was, however, found that the presence of radium was not necessary in order to obtain this result, crystals of glycerol being formed at the low temperature of the liquid air when no radium was present, just as would be expected.

Similar results were reached when gelatine was used instead of glycerol. At the low temperature of liquid air microscopic crystals were produced.

Burke then used bouillon which had been sterilized at a temperature from 130° to 140°, and found that after a couple of days a "culture" began to grow on the surface. This result was obtained whether the bouillon was immersed in liquid air or not.

The natural conclusion was that the bouillon had not been completely sterilized. To test this point check experiments were made. Some of the same bouillon was placed in tubes and subjected to exactly the same conditions as that bouillon to which the radium had been added. No "cultures" appeared in any of these tubes, while they did appear in all of the tubes to which the radium had been added.

[1] Fortnightly Review, Sept. 1905, p. 389.

In the earlier experiments the chloride of radium was used. The "cultures" were studied with respect to their power to produce other "cultures" and to inoculate other media. Burke says that for the first six weeks there was no sign of any sub-cultures. After this time there seemed to be a slight tendency toward development, but this was only very slight.

In his later experiments Burke used the bromide of radium. This was introduced on to the surface of bouillon which had been sterilized at 130° for a half-hour. The bouillon in the test-tube was protected from contamination by closing the tube in the usual way with cotton wool. Signs of the growth of the "cultures" began to manifest themselves after about a day.

These forms were not all of the same size, but differed from mere specks under the microscope to sizes of appreciable order of magnitude. Burke concludes from this that they are probably a growth from sizes too small to detect with the microscope.

These forms might, from their appearance, be calcium carbonate, but they were found to differ in properties from this substance.

At first there was no sign of any structure as seen under the microscope. Later, however, a "nucleus" manifested itself, and subdivision took place, giving rise to a new individual. This subdivision usually manifested itself after the body had reached a certain definite size.

The above properties, especially the "nucleation," "growth" and "reproduction" by division, Burke thinks are sufficient to place them in the class of living things.

These forms are obviously not bacteria. If they are living forms at all they are of a much lower order than bacteria, and Burke suggests that possibly they occupy a position between crystals and bacteria.

These forms have been termed by Burke "Radiobes."

A suggestion has been made concerning Burke's radiobes which has attracted considerable attention. It has been suggested that these forms are nothing but crystals.

Burke replies to this criticism and presents a number of arguments against the possibility of the radiobes being merely dead matter in the crystalline condition. Indeed, it is very difficult to see how the characteristic properties of the radiobes as described by Burke can be accounted for on the crystal theory. The fact that they subdivide, together with the fact that they apparently become nucleated, are difficult of explanation in terms of their crystal nature. All in all, it seems highly probable that the crystal theory of the nature of the radiobes is insufficient and will have to be abandoned.

Another suggestion has, however, been made in reference to the origin and nature of the radiobes, which deserves special attention. Sir William Ramsay [1] has offered what he considers a possible explanation of the nature of these forms. It will be remembered that Ramsay and Soddy were the first to isolate the emanation from radium, which, however, had been discovered somewhat earlier by Rutherford. They showed that it was a gas which could be condensed to a liquid by liquid air, and which gave as one of its decomposition products helium.

A solution of the emanation in water decomposes the water yielding oxygen and hydrogen. The solution of the emanation in water also has the property of coagulating albumen. In the albumen it doubtless forms at first very small, and probably ultra-microscopic aggregates or cells.

When an aqueous solution of the emanation is injected

[1] Independent, Sept. 7, 1905, p. 554.

into living matter it coagulates the albumen and becomes surrounded by a sack like the walls of a cell.

Ramsay says he thinks these facts are sufficient to account for the phenomena observed by Burke. When the radium bromide powder was sprinkled on to the gelatine it naturally sank a little distance below the surface. The emanation would act upon the water in the gelatine and decompose it, liberating oxygen and hydrogen. These bubbles of gas would become surrounded by sacks, due to the coagulating action of the emanation on the albumen. They would thus *appear like cells.*

The bubbles would at first be very small, probably of ultra-microscopic dimensions. They would gradually increase in size as more and more water was decomposed, and would thus *appear to grow.* The contents of the supposed "cell" would be gaseous — a mixture of oxygen and hydrogen, and also some of the emanation.

The emanation inclosed in the sack would continue to decompose water which would diffuse in through the covering, and gases would accumulate inside the sack until the walls would finally give way. As the mixture of hydrogen and oxygen would pass out through the rent in the walls, they would carry some of the emanation with them. This would coagulate more of the albumen with which it came in contact, and form a new cell attached to the old one. If the original cell burst in several places, we might have several new cells or buds formed from the original cell. This condition might easily be interpreted as reproduction, in the sense in which such organisms as yeast, for example, reproduce. Thus the *apparent reproducing power* of the radiobes is explained.

It is possible that such cells would show a structure on staining, since the coagulated albumen would probably stain very differently from the uncoagulated.

Whether this explanation offered by Ramsay accounts for all the phenomena observed by Burke or not, it is certainly worthy of very serious consideration.

In this same connection a fact very recently discovered by Rudge [1] should be mentioned. He also has studied the effect of salts of radium and other elements on gelatine. The salts of a number of the metals, such as barium, strontium, and lead, produce the *same effect upon sterilized gelatine* that had been observed and recorded for the salts of radium. Apparently any soluble salt of barium will produce the "radiobes," while the insoluble salts will not. As Rudge points out, these "growths" are not in any sense to be regarded as vital. He thinks that the action of radium may be due to the barium that is contained in it.

In this connection it might be pointed out that the discovery that radium would even aid the life-processes would be very remarkable in the light of what is known concerning the action of radium on living tissue. We have seen, from the brief account of the physiological action of radium, that it tends to kill living matter. This disintegrating action has been experienced by more than one experimenter who has worked with fairly pure radium salts, and its action upon cancerous tissue is probably connected with this same property.

It does not seem probable that a substance which behaves in this manner would be one that would even aid the growth of living matter, much less produce it.

ACTINIUM AND ITS DECOMPOSITION PRODUCTS

Uranium was shown by Crookes to yield uranium X, which could easily be separated from the uranium by chemical means. Similarly, Rutherford and Soddy showed that

[1] Nat., **72**, 631 (1905); **73**, 119 (1905).

thorium forms thorium X, which can be separated from thorium by very simple means. It was obvious that similar products would be looked for in the other radioactive substances.

It will be remembered that radium does not yield any substance corresponding to uranium X or thorium X, but forms apparently at once the emanation. Godlewski[1] working with Rutherford, has found such a product produced from actinium.

To the hydrochloric acid solution of the actinium, ammonia was added. A reddish-brown precipitate was formed which was probably the hydroxide. The filtrate was evaporated to dryness, and the ammonium salts driven off by ignition, when a small black residue remained, which became white on heating.

This residue was found to be *intensely radioactive* as compared with the actinium from which it was separated. The activity was found to decrease slowly with time, according to an exponential law.

The actinium from which the intensely radioactive product had been separated, was at first almost non-radioactive. It recovered its radioactivity with time, the recovery curve being the inverse of the decay curve of the residue.

It will be seen that the above results are strictly analogous to those obtained with uranium and thorium. From the analogy to thorium X, the above, highly active product was termed actinium X, and assigned the symbol AcX.

The radioactivity of actinium X, when first separated from the actinium, was *more than one hundred times* as great as that of the actinium itself. The residue obtained by evaporating the filtrate, as above described, is not all actin-

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[1] Phil. Mag., **10**, 35 (1905).

ium X, but consists chiefly of non-radioactive material, which is probably some of the rare earths.

The analogy between uranium, thorium, and actinium is, as we have seen, very striking. There is, however, one marked difference. After thorium X is removed there remains in the thorium a residual activity, which amounts to about twenty-five per cent. of the total radioactivity possessed by normal thorium.

After actinium X is removed from actinium, the activity of the remaining actinium, when tested immediately, is only about five per cent. of what it is in the normal substance.

Godlewski tried to remove this small residual activity by repeatedly precipitating the actinium solution with ammonia. Eight precipitations were made in seven hours. The residual activity, however, still remained. This was probably due to the presence of a small amount of actinium X, which could not be separated from actinium. The latter when freed from actinium X is perfectly non-radioactive. This shows that the production of actinium X from actinium is, as we say, a "rayless change," no radiation of any kind being given off.

Actinium X was shown to give out α, β and γ rays. That the β rays come directly from actinium X, and not from the excited activity resulting from the deposit of the emanation, is made highly probable by the following facts: The curves of decay of the activity of actinium X are the same, whether the activity is measured by the α or the β rays. It is also pointed out that the activity of actinium X, measured by the β rays directly after strong heating, which would remove all the cause of excited activity, has a large value even at the beginning. This would not be the case if the β rays came from the excited or induced activity.

The problem of the *origin of the emanation* in actinium was then attacked. It will be remembered that the thorium emanation comes from thorium X. Does the actinium emanation come from actinium X? This question can be easily answered.

Remove the emanation from actinium containing actinium X, and test the amount by the activity. Then remove the emanation from an equal amount of actinium from which the actinium X has been separated, and test its activity. The result is very satisfactory.

The actinium from which actinium X has been separated gives practically no emanation. Further, the amount of the emanation increases as the amount of actinium X increases, and decreases at the same rate that the activity, or as actinium X decreases.

Godlewski points out that the emanation being present only when actinium X is present, and being always proportional to the amount of actinium X, it must be the product of actinium X.

The products of actinium that have thus far been shown to exist, are the following. Actinium yields actinium X, the change being a rayless one. Actinium X gives out α, β and γ rays and yields the actinium emanation. The actinium emanation gives out α particles and produces actinium A. Actinium A yields actinium B, the change being rayless. Actinium B gives out α, β and γ rays, and yields actinium C.

Godlewski also shows that the β rays from actinium differ from the β rays from other radioactive substances. In the first place they are completely homogeneous, and in the second, have less than half the penetrating power of the β rays emitted by other radioactive substances.

He also shows that the γ rays from actinium have only

about one-fourth the penetrating power of the γ rays from radium.

EMANIUM

During the last year or two a number of articles have appeared on a supposedly new radioactive substance called *emanium*. It was discovered in pitchblende by Giesel, and was found to be related chemically to the elements of the cerite group, and especially to lanthanum and cerium.

The dehydrated chloride or bromide shows a discontinuous phosphorescent spectrum of three lines. Glass in which the substance was preserved for some months was colored violet. Paper was browned and decomposed. After the maximum activity was reached the activity of the solid substance underwent no further change. Giesel[1] concluded in his earlier work that this substance is a new radioactive element. He thought that the results could not be accounted for as due to any induced activity resulting from contact with radium. When a current of air was blown over the preparation of the supposedly new substance and then against a phosphorescent screen, bright scintillations or sparks made their appearance, that were more distinct and larger than in the case of radium, and the effect was more striking than in the ordinary spinthariscope.

This strongly radioactive substance, supposed by Giesel to be a new radioactive element, was named by him *emanium*.

He, however, pointed out about a year ago that it was possible that emanium was identical with the actinium discovered by Debierne. At that time, however, there was not sufficient known about the properties of the two substances to determine whether they were identical or not.

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[1] Ber. d. deutsch. chem. Gesell., **37,** 1696 and 3963 (1904); **38,** 775 (1905).

Debierne undertook a comparative study of actinium and emanium, and concluded that the two were identical. Giesel, however, points out that there are certain differences in the properties of the two substances that need explanation before we can regard the two as identical. The induced radioactivity produced by emanium falls to half-value in 34.4 minutes, while that of actinium requires 40 minutes to decay to half-value.

He also points out that the three lines observed in the phosphorescent spectrum of emanium, having the wavelengths 4885.4, 5300, and 5909, respectively, had not at that time been observed in actinium. Further, since these lines could not be identified with those of any known element, it seemed fair to conclude that they were due to a new element.

Giesel studied the activity of emanium, and showed that the emanation was not driven out by heating or solution as with radium, and concluded that there was a solid, non-volatile substance formed.

Subsequent work, however, has shown that the three lines mentioned above are really not new lines at all, which can be referred to a new element, but were produced by one of the didymia that was present. This invalidates one of the lines of reasoning which led Giesel to conclude that he was dealing with a new substance. He separated the active constituent or constituents from emanium, in a manner analogous to that employed by Rutherford in the case of thorium. He found most of the activity of the emanium in the small residue that remained when the solutions containing emanium were precipitated with ammonia. On account of the analogy with thorium X, Giesel termed this active residue *emanium* X.

He showed further that when emanium X has been sepa-

rated from emanium, more emanium X is *continually being formed*. This again is strictly analogous to the condition of things in thorium. It was also established that most of the activity of emanium is due to the emanium X that is present in it.

The question as to the identity of emanium and actinium was taken up quite recently by Hahn and Sackur.[1] It will be recalled that the argument advanced by Giesel based upon spectrum analysis, in favor of the two substances being different, had been shown to be untenable — the lines supposed by him to be produced by emanium being really those of one of the didymia.

The second argument advanced by Giesel to show that these two substances are different, was based upon the different amounts of time required for the induced radio-activities produced by the two substances to decay to half their initial value. These measurements have been repeated by Hahn and Sackur, with the result that the amounts of time required in the two cases *are the same*.

These authors have also determined the amount of time required for the emanation itself from the two substances to decay to half-value. They find that the time in the two cases is *exactly the same*, to within the limits of experimental error.

From these facts they conclude that the *actinium of Debierne and the emanium of Giesel are probably identical.*

New light seems to have been thrown on the relation between actinium and emanium by Marckwald.[2] He thinks that he has satisfactorily solved the problem. The rare earths obtained from the radium mother-liquor were transformed into chlorides, and the thorium precipitated

[1] Ber. d. deutsch. chem. Gesell., **38**, 1943 (1905).
[2] Ber. d. deutsch. chem. Gesell., **38**, 2264 (1905).

by thiosulphate. This thorium showed strong emanating power and contained the actinium of Debierne. From the solution cerium was first precipitated, and then the didymia and lanthanum as oxalates, which were transformed into oxides. Neither the cerium nor the mixture of the didymia and lanthanum showed any considerable emanating power.

The thorium was then purified by subjecting it to a number of processes, but the emanating substance clung to the thorium in all of these operations.

The activity of this actinium which accompanied the thorium was studied for several months and *was found to decrease*. The mixture of the didymia and lanthanum, on the contrary, *acquired greater and greater emanating power with time* — their emanating power increasing in the same ratio as that of the actinium in the thorium decreased. The author points out that this is analogous to the case of thorium and thorium X.

The explanation of these facts seems very simple. The radioactive substance that accompanies the lanthanum gives off no emanation. It, however, decomposes into a second substance, which in its chemical reactions resembles thorium. When the latter substance undergoes further decomposition a strong emanation results.

To test the correctness of this interpretation the following experiment was performed: A half-gram of pure thorium oxide was added to eighteen grams of the didymia-lanthanum mixture, which had stood until it emanated strongly. The whole was then dissolved in hydrochloric acid and the thorium again precipitated by thiosulphate. The thorium precipitated now contained nearly all the emanating power; the solution of the didymia-lanthanum mixture contained very little of the emanation.

The conclusion seems necessary that there is something

in the didymia-lanthanum mixture *which yields a substance* closely allied chemically to thorium, and which has strong emanating power.

Emanium and actinium are, then, not identical. Emanium undergoes decomposition and yields actinium — *emanium is the parent of actinium.*

As Marckwald points out, it is unfortunate that Giesel should have chosen the name emanium for the substance that accompanies the didymia-lanthanum mixture, since this substance has no emanating power whatsoever.

This is after all a minor matter. The important point is that the relation between emanium and actinium seems at last to have been cleared up.

RADIOTHORIUM — A NEW RADIOACTIVE ELEMENT

A new radioactive element has recently been described by Sir William Ramsay.[1] Reference has been made to this substance somewhat earlier by students of Ramsay, but the first satisfactory account of the discovery and the element discovered has just been given by Ramsay himself. It was found in a mineral obtained from Ceylon. Ramsay obtained about two hundred and fifty kilograms of the mineral, having become interested in it on account of the large amount of helium that it contained. One gram of the mineral gave about nine cubic centimetres of helium gas, which was between three and four times the amount obtained from cleveite.

It is of interest to know that Ramsay has already obtained from the mineral about one cubic metre of helium gas, and we may look for some interesting results in reference to the properties of this substance. It is well known that this is the only gas that has thus far not been liquefied,

[1] Journ. de Chim. Phys., **3**, 617 (1905).

and this is mainly due to the fact that a sufficient quantity had not previously been obtained. It is highly probable that with the amount of helium now at disposal, it will be possible to convert it into the liquid state, and then the last of the most resistant gases will have succumbed to modern methods of liquefaction. The new element was obtained from the mineral, which was named "thorianite," in the following manner: The mineral was fused with sodium disulphate. The residue insoluble in water was treated with dilute, boiling hydrochloric acid. The insoluble sulphates were then fused with sodium carbonate, which transformed them into carbonates. The barium carbonate obtained was strongly radioactive and contained the radioactive matter in the mineral. The radium was separated by the method devised by Giesel, *i.e.*, by fractional crystallization of the bromides. It soon became obvious that there was present a radioactive constituent other than radium. Its bromide was even more soluble than the bromide of barium.

The chemical properties of the new substance show that it is not identical with any known element. It resembles in general the rare earths. It is to be distinguished chemically from radium in that it forms a soluble sulphate, and from thorium in that its oxalate is insoluble in an excess of ammonium oxalate. The new substance gives off an emanation, which has the same properties as the thorium emanation. Its rate of decay is the same as that of the thorium emanation, and the excited activity produced by the emanation from the new substance diminishes at the same rate as that produced by the emanation from thorium. The oxide, after being strongly heated, but not otherwise, glows in the dark. A similar result is obtained when one of the salts is cooled in liquid air, but not to the same extent.

When a few milligrams of the new substance are wrapped in paper and placed in front of a screen of zinc sulphide, a phenomenon manifests itself similar to that observed in the spinthariscope. Ramsay has measured the radioactivity of radiothorium. In making these measurements solutions of its salts were used, since these gave more constant results than the solid salts. It was found that the amount of the emanation obtainable from a given quantity of the radiothorium was equal to that obtainable from *five hundred thousand* times as much thorium. The relative powers of radiothorium and radium to discharge the electroscope have also been tested. It was found that radiothorium has apparently about half the discharging value of radium.

Sir William Ramsay summarizes the results that he has obtained with radiothorium as follows:

The emanation given off by radiothorium is identical with that given off by salts of thorium. The quantity, as we have seen, is infinitesimal in the case of thorium compared with the amount given off by radiothorium. The conclusion is that ordinary thorium probably contains a trace of radiothorium to which it owes its radioactivity. Ramsay announces that he has already succeeded in separating a part of the radioactivity from the thorium, by adding to the thorium salt a salt of barium, and then adding sulphuric acid. A part of the radiothorium is probably brought down along with the barium salt.

Analogous to the decomposition products of uranium, Ramsay suggests the following scheme as representing the probable decomposition products of thorium.

Inactive thorium — radiothorium — thorium X — emanation — thorium A — thorium B — ? — helium.

There seems to be no doubt, according to Ramsay, that

the helium found in thorianite is produced from the radio-
thorium present in that mineral.

CONCLUSION

The investigations, of which a general account has been
given in these chapters, mark a new epoch in the develop-
ment of the physical sciences. Some of the results obtained
are as important from the standpoint of the physical chemist
as from that of the physicist.

Facts have been brought to light which are of a character
that are very different from anything hitherto known. *The
existence of extremely penetrating forms of radiation, the
instability of the chemical atom, the formation of one ele-
mentary substance from another, the existence of a form of
matter that can charge itself electrically, that can light itself,
and that can give out an amount of heat that is almost
inconceivably great,* are some of the facts to which we
must now adapt ourselves.

These are magnificent developments with which to open
the new century. Probably still more surprising facts are
awaiting men of science before its close. It seems not too
much to predict that as the nineteenth century surpassed
the preceding eighteen in the development of scientific
knowledge and the discovery of truth, just so the twentieth
century will exceed them all in the gifts of pure science to
the store of human knowledge.

The wave of scientific investigation for its own sake that
has recently swept over the entire civilized earth, must yield
a rich harvest to those who shall be permitted to reap it.

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